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The research supported by my grant from AFOSR this year completed some of the projects outlined in the first annual report and initiated some new ones. The focus remained on the visual processing of features and objects, the role of spatial attention and the representation of complex visual patterns in perception and memory. Studies of visual search explored the coding of features at potentially more abstract levels than simple luminance filters: Among the features studied were orientation (for lines, dot pairs and edges), orientation and size (for shapes whose boundaries were defined by discontinuities of texture, motion and depth), and illusory contours. Another series of experiments tested the mechanisms underlying the coding of feature conjunctions, using evidence from search latencies and illusory

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conjunction errors. The results led to a proposed revision of my earlier feature integration theory. Two other studies looked at memory for visual patterns. One (with Alfred Vieira) studied the effects of prolonged practice ([redacted] thousands of trials) on the coding of visual patterns. At the other extreme, an experiment (with Gail Musen) explored the effects on memory of just one to five presentations of similar patterns. In both cases, we found striking specificity in the coding of these meaningless shapes and in their effects on subjects' later experiences with the same stimuli. Patterned conjunctions of lines, once formed, appear to persist in visual memory and to facilitate their later re-perception provided that the same task and context are also reinstated.

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VISUAL INFORMATION PROCESSING IN THE PERCEPTION OF FEATURES AND OBJECTS

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5th January, 1989

Second Annual Technical Report

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Prepared for
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Summary

The research supported by my grant from AFOSR this year completed some of the projects outlined in the first annual report and initiated some new ones. The focus remained on the visual processing of features and objects, the role of spatial attention and the representation of complex visual patterns in perception and memory. Studies of visual search explored the coding of features at potentially more abstract levels than simple luminance filters: Among the features studied were orientation (for lines, dot pairs and edges), orientation and size (for shapes whose boundaries were defined by discontinuities of texture, motion and depth), and illusory contours. Another series of experiments tested the mechanisms underlying the coding of feature conjunctions, using evidence from search latencies and illusory conjunction errors. The results led to a proposed revision of my earlier feature integration theory. Two other studies looked at memory for visual patterns. One (with Alfred Vieira) studied the effects of prolonged practice (thousands of trials) on the coding of visual patterns. At the other extreme, an experiment (with Gail Musen) explored the effects on memory of just one to five presentations of similar patterns. In both cases, we found striking specificity in the coding of these meaningless shapes and in their effects on subjects' later experiences with the same stimuli. Patterned conjunctions of lines, once formed, appear to persist in visual memory and to facilitate their later re-perception provided that the same task and context are also reinstated.

Administration and Personnel

Since January 1st, 1988, the following personnel have been partly supported by the grant (in addition to myself during the Summer months): Sharon Sato (technical assistant), Ephram Cohen (part-time programmer), and Sherlyn Jimenez (undergraduate clerical and research assistant). Sharon Sato was promoted one step on the technician's scale, in view of her excellent performance, her experience and the programming skills she has acquired. She will leave the laboratory this summer to get married, and will have to be replaced.

The following graduate students have worked on projects under my supervision: Gail Musen, who was awarded her Ph.D. this December; Alfred Vieira and Marcia Grabowecky who are both working for the Qualifying Exam and preparing their thesis proposals, Kathy O'Connell and Elizabeth Beiring who completed their first year projects, and Meg Wilson who began in the Graduate Program in September. Kathy O'Connell moved to another lab in August to learn some new techniques, and may return for her Ph.D. Elizabeth Beiring left the program in May to return to the East coast. Two of the graduate students obtained N.S.F. fellowships (Kathy O'Connell and Meg Wilson), one was supported by the Canadian Natural Science and Engineering Research Council (Marcia Grabowecky) and two were supported by the Sloan foundation grant to Cognitive Science at Berkeley (Gail Musen and Alfred Vieira). The Sloan grant ends in May and Marcia's NSERC fellowhip also ends soon.

Whereas I have not had to support any of the students on the AFOSR grant in the past year, the situation is likely to change this year. I have applied to carry over the unspent funds to meet the extra research assistant support that is likely to be needed. I have also applied to spend part of the money on a piece of equipment (a Minolta Chroma-Meter) to allow us quickly and easily to measure the luminance and chromaticity coordinates of the stimuli we use and to calibrate the four displays we use in the research.

Research Completed and In Progress

In my report a year ago, I outlined a number of different research projects that were under way at that time. During the year we continued work in each of these areas, completing some of them. We also initiated some new experiments on moving objects (with a new graduate student, Meg Wilson) and on similarity effects in search. Again, I will organize this report under different headings, although all concern the central question how we perceive objects and represent them in memory.

Features in Early Vision

It is generally accepted that some forms of perceptual processing occur independently of attention, automatically and in parallel across the field. These early levels of visual analysis seem to extract a number of simple properties or features in a set of partly modular sub-systems or channels, whose outputs are later recombined, under attentional control, to form representations of objects in the real world (see, for example, Julesz, 1985; Treisman and Gormican, 1988).

1) Coding of orientation.

Kathy O'Connell and I completed a series of experiments probing the nature of the representation formed of orientation at early stages of visual coding. It is known that a target line that differs in orientation from a set of background or distractor lines will "pop out" in a search task, allowing equally fast detection whatever the number of items in the display. We asked whether the orientation difference is coded in an analogue way (for example, by filters like the oriented receptive fields described by Hubel and Wiesel (1967), that sum the energy at a particular orientation), or whether it is coded more abstractly or symbolically, as suggested by Marr (1982). For example, would the same representation be formed for the orientation of a virtual line linking a pair of dots as for a solid line, or an edge? If so, would the direction of contrast need to be the same, both between lines or dot pairs and within dot pairs? We used a conjunction search paradigm to test whether shared orientations cause interference across different types of oriented stimuli. In a typical experiment, subjects might search for a line tilted right among dot pairs tilted right and lines tilted left. If the same orientation codes are activated by dot pairs and by lines, the target would be defined only by a conjunction of orientation (right) and "medium" (line rather than dots) and should therefore require serial checking with focused attention. This is what I found in an earlier study (Treisman, 1985). Kathy O'Connell and I extended the

paradigm to test bicontrast dot pairs (one black and one white on a grey background) among mixed black and white lines. We found that orientation does not seem to be coded in parallel for bi-contrast dot pairs in the same way as it is for uni-contrast pairs. Although subjects could find the pair with the target orientation, the search process appeared to be serial.

We also ran an experiment following the same logic, testing whether lines and edges share the same orientation code. Here we found clear evidence that they do. Both conjunction conditions gave apparently serial search. In addition, the results suggested an asymmetry. The edge targets were found more slowly among lines of the same orientation than the reverse. This is consistent with physiological results: cells with asymmetric receptive fields ("edge detectors") will also respond to lines more than those with symmetric receptive fields will respond to edges. These results are consistent with the conclusion that parallel 'pop-out' for orientation targets is mediated by spatial luminance filters like the cells described by Hubel and Wiesel (1968). However, the results described in the next section suggest this is not a complete account of orientation coding.

2) Different channels coding features of shape.

Together with Patrick Cavanagh and Martin Arguin, I completed a paper describing a series of experiments on search for targets differing in size or orientation, where the shapes (both targets and distractors) were defined by discontinuities in a number of other channels or media. We tested five different channels (previously studied in other perceptual tasks by Cavanagh): luminance, color, motion, stereoscopic depth and texture. We found parallel detection of size and orientation targets in every case except perhaps stereoscopic depth, where the discontinuities themselves were hardest to discriminate. We also found the same search asymmetry between vertical and tilted targets in the orientation domain across all the channels. The results suggest that the same vocabulary of shape-defining features may be extracted within a number of different media. A paper describing the results (copy enclosed) has been submitted to Journal of Experimental Psychology: Human Perception and Performance.

3) Feature similarity effects in search.

Duncan and Humphreys (in preparation) have recently proposed a "resemblance theory" of search, in which they claim that search latencies are completely determined by two measures of similarity: latencies are assumed to increase (a) with the similarity between target and distractors, and (b) with the dissimilarity between different distractors. They suggest that those two factors can also account for the

difficulty of conjunction relative to feature targets in visual search. I agree with them that both forms of similarity can in some cases increase the difficulty of search, but I think there may be an additional difficulty in conjoining features. We attempted to test this belief by matching the similarity structure as closely as possible and comparing search for feature and for conjunction targets. Figure 1 specifies the stimuli we tested. The target was always a blue vertical bar (labelled 33 in the figure). The distractor pairs used on any trial could be chosen either to make the target depend on a conjunction, or to give it a unique value on one or both dimensions. We tested a number of distractor pairs, all of which left the target with a unique feature, and four pairs for which the target was specified only by a conjunction of features. The conjunction search pairs were 31 and 13, 13 and 35, 35 and 53, and 53 and 31. The feature search conditions were (1) search with pairs that differed maximally on a single feature, either color or orientation; the pairs here were (31 and 35; 13 and 53), so that the average "city block" distances in the two-dimensional space between the conjunction target and distractors and the feature target and distractors were the same; (2) distractor pairs that differed in two features, both from each other and from the target; the pairs here were 22 and 44; 24 and 42, where the city block distance from target to distractor was again the same as for the conjunction targets and the difference between the distractors was about the same as for the conjunction condition; (3) finally, we combined the two previous feature search conditions, using pairs 31 and 24; 31 and 44; 13 and 42, 13 and 44; 35 and 22; 35 and 42; 53 and 24; 53 and 22. We ran two experiments: both included the conjunction search condition; one also had feature search condition (1); the other had feature search conditions (2) and (3). On any trial, the subject did not know which distractors pairs would be present. In each case, the feature conditions gave faster latencies and flatter slopes with display size than the conjunction targets (see Figure 2).

If the similarity structure is to explain the greater difficulty of conjunction search, it must be defined in a way which makes it difficult or impossible to distinguish from the conjunction hypothesis; for example, it would need to specify that the distractors must each share a different relevant property with the target, which as a result will differ only (a) in the way it conjoins the relevant features, or (b) in the features that it lacks and that are present in the distractors.

4) <u>Illusory contours as features?</u>

Marcia Grabowecky and I continued our investigation of illusory contours in search and in divided attention. We

found no evidence that an illusory triangle (formed by three appropriately aligned pacman figures) could be detected in parallel in a search display (despite the physiological evidence by Van der Heydt et al (1985) that cells in cortical area V2 in the monkey responded to such contours). However, we also found that ratings of the clarity of the illusory contours drop sharply with distance from the fovea. This makes it hard to separate the need for fixation of the eyes from the need for serial "fixations" of attention.

We now plan to separate the effects of attention load and fixation by using rapid serial visual presentation and a competing attention-demanding task with peripheral stimuli that do not require fixation. This task was developed in another context by Meg Wilson and me (see section II, 4 for a description). We can then test whether the attention-demanding but non-foveal task makes it harder to detect an illusory triangle in a central sequence of random pacman triples. If it does, this would strengthen the hypothesis that illusory contours depend on central attentional processing to construct the representation of a single occluding figure from the separate occluded parts. The physiological coding that can be recorded from area V2 could reflect a contribution from centrifugal pathways rather than the immediate results of early coding in an afferent pathway.

II. The Perception of Conjunctions.

The theory I have developed over the past eight years proposes that once the various features present have been detected and grouped within separate modular maps, they are conjoined to form representations of the various objects in the scene by a process of serial scanning with focused attention. Support for this claim comes from the linear increase in latencies with increases in display size in search for conjunction targets, from the occurrence of illusory conjunctions when attention is overloaded, from the large benefits in identification accuracy that result from advance cues to the relevant location and from the dependence of correct identification on correct localization for conjunction stimuli.

1) Conjunction search.

One of these sources of evidence has recently been challenged, however. Nakayama (1986) and Wolfe, Cave and Franzel (1989) have found apparently parallel search for conjunction targets when their component features are highly discriminable colors, orientations, shapes, sizes or directions of motion. In order to try to understand the discrepancy between these results and my earlier findings, Sharon Sato and I completed a series of studies exploring conjunction search with highly discriminable features. In

last year's report, I described an experiment testing all possible pairings of highly discriminable values on the dimensions of color, size, orientation and direction of motion. As previously found by Nakayama (1986) and more recently by Wolfe, Cave and Franzel (1989), the search rates we obtained were substantially higher than in my earlier research, and in a few cases search seemed to reflect almost parallel coding. In addition, we found evidence consistent with the idea that each dimension contributed a constant to the slope of the search function.

We proposed a modification to my original feature integration theory to explain these results. The suggestion is that spatial attention can be directed in two different ways: (1) as suggested in the earlier theory, it can scan locations serially through a selective "window" limited to one contiguous area at a time; (2) it can inhibit disparate locations in parallel on the basis of the non-target features they contain, perhaps by control through the separate feature maps I postulated as the output of parallel, preattentive processing. Since then, we have run three further experiments testing the revised model: (1) we showed that the rapid search rates depend on prior knowledge of the targets, as they should to allow inhibition based on non-target features; (2) that search is faster when the conjunction target differs in two features from each distractor than when it differs only in one (cf Wolfe et al. 1989); finally, we found that search is slower when the distractors are more heterogeneous, even when their average similarity to the target decreased. This is consistent with the idea that rapid search depends on inhibiting locations with non-target features rather than activating those containing target features.

We spent some time preparing a paper describing the five experiments and developing the revised theory of feature integration that we believe can reconcile the new findings with my earlier ones. The paper entitled "Conjunction Search Revisited" (copy enclosed) has been submitted to Journal of Experimental Psychology: Human Perception and Performance.

(2) Illusory conjunctions.

The feature-integration theory we proposed in 1980 and 1982 was an attempt to explain data from a number of different paradigms, not only from visual search. Some of the strongest support for the idea came from the occurrence of illusory conjunctions of features when attention is overloaded and serial processing is prevented. Given the flatter search functions obtained with highly discriminable features, it seemed important to test whether illusory conjunctions would still occur with similar simple and discriminable computer-generated stimuli as with the earlier tachistoscopic colored letters and shapes used by Treisman

and Schmidt (1982). Sato and I have recently confirmed that they do occur, about as frequently as with the earlier colored letter displays, with the dimensions of color, orientation and "medium" (i.e. outline, filled and broken rectangles).

Figure 3 shows a typical display. Immediately after the display, a mask, together with a bar-marker appeared, indicating which of the four stimuli should be reported, or whether the digits should be reported. By sampling the digits on separate trials from the colored bars, we reduced the possibility that decay in memory would cause conjunction errors. The digits were cued on 30% of the trials but were given much higher priority in the instructions to ensure that attention would be spread across the display rather than focused on any single rectangle. In each case for each of the four features of the cued item, one incorrect value was present in the display - either once or three times - and one was not present.

So far we have tested nine subjects; they reported an illusory conjunction on average on 25% of trials (this is the difference between the erroneous reports of a feature that was present in a non-cued location and a feature not present in the display). In the earlier Treisman and Schmidt experiment with colored letters the proportion of trials that gave illusory conjunctions of shape and color was 24%. The only dimension for which we found no clear evidence of illusory migrations in the present experiment was size: one reason might be that the size values were too hard to identify with the brief exposures we used. Subjects failed to identify 47% of the sizes, compared to 34% of the media, 40% of the orientations and only 12% of the colors.

In this experiment we also asked a further question not previously tested: would the number of replications of a feature affect the probability that any one of them would migrate to form an illusory conjunction. We found no effect for orientation or medium, but subjects were somewhat less likely to form an illusory conjunction involving a color that was replicated three times than to form one with a color that was unique in the display. The expected ratio would be 1 to 1 if each replication of the repeated color were as likely to migrate as a single non-replicated color; however, the observed ratio was 1 to 2, with repeated colors forming illusory conjunctions only half as often as unrepeated ones. This might reflect a form of "repetition blindness" (Kanwisher, 1987) making subjects more likely both to see and to correctly locate a target in a unique color than one of several tokens of the same repeated color type. The ratio of omissions for the repeated target color relative to the non-repeated colors was 4 to 1 rather than the expected 3 to 1. (There were 3 times as many trials in which any target feature was replicated as in which it was unique.) The effect seems then, to be due to the fact that

subjects were more likely to see the color of the target item correctly when it was unique than when it was shared by three other items. Interestingly, the other features did not induce the same repetition blindness.

(3) Attention span with moving objects.

Together with a new graduate student, Meg Wilson, I have begun some research in a paradigm developed by Pylyshyn and Storm (1989) exploring subjects' ability to keep track of several randomly moving, otherwise identical objects. Pylyshyn and Storm found that subjects could keep track of up to 4 among 8 identical randomly moving shapes, so that when probed with one of the eight they could distinguish with about 90% accuracy whether it was one of their assigned targets or a distractor. This is an interesting finding in relation to the concept of "object files" that Kahneman and I proposed (1984); it suggests that once four separate object files have been set up, they can be maintained without devoting focused attention to each of the four. Pylyshyn (1988) has proposed the notion of a limited number of "FINSTs" or indices, which can preattentively maintain the spatial addresses of visual tokens as they or the observer move.

Meg Wilson decided to test how far the task really is independent of attention, by seeing whether it is disrupted by a concurrent attention-demanding task. We spent some time developing a task which would not also require visual fixation, (since we have no equipment to measure eye movements, and we wanted to leave subjects free to fixate where they wished). The attention task we developed involves monitoring a changing sequence of colors and textures in a broad frame (around the foveal area in which the objects move) in order to detect the occurrence of a particular conjunction of color and texture (eg. red stripes) in a rapid sequence of other combinations of color and texture. At any one time, only one color and one texture are present, so there is no need to localize or fixate the stimuli in space. Instead they must be conjoined repeatedly for each brief interval of time. We plan to compare subjects' ability to track the moving objects without a concurrent task, with a conjunction-monitoring task (e.g. watch the frame for red stripes in a sequence containing red spots and green stripes), and with a feature-monitoring task (e.g. watch the frame for blue <u>or</u> plaid in the same sequence of red spots and green stripes). We also plan to integrate the stimuli for the concurrent task with those for the moving object task, to see if it is easier to divide attention when it is the moving objects that change color and texture than when it is the surrounding frame.

The experiment may throw light on the mechanisms of attention as well as on those involved in tracking and maintaining representations of moving object tokens.

Attention may be limited in two different ways: (1) the number of spatially distributed objects it can encompass at any one time; (2) the number of tasks that can be performed at once, even on the same objects. The kind of attention I have studied within the framework of feature integration theory has been the spatially selective "window" that I claim specifies which features belong together. It is not clear that moving a 'mental' window around a scene need compete with temporally serial checking of a sequence of color-texture pairs. At most one object file (or FINST in Pylyshyn's mode) would be taken up by the frame task. No extra files or FINSTS would be involved in the version in which the moving objects themselves change color and texture. The results may indicate, therefore, whether attention capacity is required to conjoin features as well as to select spatially which features to conjoin.

III. Memory for Visual Patterns.

Once focused attention has established an integrated representation for a complex combination of parts or properties, the representation presumably becomes part of our visual memory. It is of interest to study how it persists or changes over time and how it affects the perceptual coding of later presentations of the same pattern.

(1) Perceptual learning.

In last year's report, I described a study that Alfred Vieira and I conducted on the effects of prolonged practice in search for arbitrary sets of letters among other letters. We found surprisingly little transfer of the large practice benefit from search to any other task. The results gave no support to the hypothesis that automatization in search tasks reflects a change in the perceptual representaion of the targets, making a unitary feature of what had initially been coded as a conjunction of parts. However, letters may be a special case: they are highly familiar already and may be detected through global features, the effect of practice in search may be simply to increase the salience of the correct set of global features distinguishing the specified targets from the distractors.

We therefore conducted another study of search automatization using more complex arbitrary, meaningless shapes (six-line figures in a 3 x 3 dot matrix). Again, we obtained a very large increase in search rates over 16 sessions of practice. We then explored the degree of transfer to a large number of other perceptual tasks, including mental rotation, perception of apparent motion, iconic memory, threshold in same-different matching, finding parts in wholes, and ratings of clarity, goodness and likability. Again, we found remarkably little transfer. In

an attempt to find out what was learned, we also looked at transfer to variations within the search task itself. We found a striking specificity to the particular learned targets, less to the learned distractors, and even a significant decrement when we changed irrelevant aspects of the display, such as the direction of contrast (black on green vs. green on black) or the spatial configuration of the displays. The results are consistent with an account of automatization in terms of the accumulation of specific exemplars of previous trials in memory (Logan, 1988). A paper describing this study was presented at the meeting of the Psychonomic Society in November, 1988 (copy enclosed).

The last major project we completed this year was Gail Musen's Ph.D. dissertation and a joint paper (copy enclosed) reporting one of the experiments that we did together; we have submitted the paper to Journal of Experimental Psychology: Learning, Memory and Cognition. The topic was a comparison of implicit and explicit memory for unfamiliar non-verbal patterns. Most work on visual memory has used either words or pictures of familiar objects. Explicit memory is typically measured by recall or recognition, whereas implicit memory is measured by priming of performance in a non-memory task such as perception near threshold or word-fragment completion (Tulving, Schacter and Stark, 1982). If performance is better for previously studied items, this is taken to reflect memory without awareness of the earlier presentation. The two measures have been shown to be independent with familiar verbal stimuli. The standard explanation has been that priming reflects the persisting activation of pre-existing representations or nodes in a semantic memory network, whereas recall and recognition depend on separate episodic memory traces.

In our experiment, we used the same type of line patterns as in Vieira's experiment, but with 5 rather than 6 lines. We found clear perceptual priming after a single presentation of 50 of these novel visual patterns. The task was to draw each pattern immediately after it was briefly flashed and followed by a mask. The priming measure was the difference in the number correct for previously studied patterns and for new ones. The priming did not increase much with four further presentations or decrease much with the passage of time (up to a month), whereas recognition memory for the same patterns showed substantial effects of both. Moreover, performance was stochastically independent for the same patterns in the recognition and in the priming tasks. We also directly tested episodic memory for the patterns by showing half of the previously studied patterns one more time and seeing whether they differed from the other half by either explicit or implicit memory measures. We found excellent recognition performance in the task of discriminating the re-presented items from the others, and no difference at all in the priming they produced.

Gail ran two further experiments for her dissertation: one showed a dramatic effect of verbal coding on recognition memory and no effect on priming; the other showed somewhat reduced priming when the study time was reduced from 10 seconds per pattern to 1 second, but a much greater reduction in recognition memory.

These memory dissociations with previously unfamiliar stimuli pose a problem for the account in terms of the separation of episodic from semantic memory, since no pre-existing representations of our line patterns were available to be reactivated and mediate priming. On the other hand, the stochastic independence and functional dissociations pose problems for an account that suggests that the same episodic memory traces mediate both tasks. Perhaps a new representation of a "type" can be set up in a single presentation; later recurrences are then matched to this type to facilitate perceptual identification, but also lay down separate traces for each token of the type, to mediate later explicit memory tasks, like recall, recognition or familiarity judgements.

Gail Musen has now moved to a post-doc with Larry Squire at UCSD, where she will test amnesic patients in the same task, to see if they show the same selective loss of explicit but not implicit memory with visual patterns as they do with verbal stimuli.

Papers published or in press

Treisman, A. and Gormican, S. 1988. Feature analysis in early vision: Evidence from search asymmetries. Psychological Review, 95, 15-48. (Copy sent in June)

Treisman, A., 1988. Features and objects: the Fourteenth Bartlett memorial lecture. Quarterly Journal of Experimental Psychology, 40A, (2), 201-237. (Copy sent in June)

Treisman, A., Cavanagh, P., Ramachandran, V. and Van der Heydt, R. The perception of form: striate cortex and beyond. To appear in Spillman, L. and Werner, J. (Eds.) Neurophysiological foundations of visual perception, Academic Press.

Papers submitted

Treisman, A. and Sato, S. Conjunction search revisited.

Cavanagh, P., Arguin, M. and Treisman, A. Effects of stimulus domain on visual search for orientation and size features.

Musen, G. and Treisman, A. Implicit and explicit memory for visual patterns.

Papers in preparation

Kahneman, D., Treisman, A. and Gibbs, B. The integration of information in object-specific representations.

Vieira, A. and Treisman, A. Automatic search: changing perception or procedures.

Lectures and conference papers presented in 1988

Anne Treisman

January. Colloquium at U.C. Santa Cruz.

March. Invited paper to AAAI Symposium, Stanford, California.

March. Invited paper to Howard Hughes Vision conference, Miami.

April. Invited address to W.P.A., San Francisco.

June. Paper to workshop on 'Exploratory Vision,' Ann Arbor, Michigan.
Lecture to McDonnell Summer Institute, on Cognitive Neuroscience, Harvard University.

September. Talk to AFOSR Workshop on attention, Colorado Springs.

October. Paper to Canadian Institute of Advanced Research Annual Meeting, Whistler, British Columbia, Canada.

November. Vieira and Treisman. Paper to Psychonomic Society, Chicago.
Colloquium at U.C. San Diego.

Talks by graduate students

April. Gail Musen, paper to W.P.A. San Francisco.

May. Gail Musen, talk to joint Berkeley-Stanford graduate student conference.
Alfred Vieira, talk to joint Berkeley-Stanford graduate student conference.
Marcia Grabowecky, talk to joint Berkeley-Stanford graduate student conference.
Elizabeth Beiring, talk to joint Berkeley-Stanford graduate student conference.

REFERENCES

Hubel, D.H., & Wiesel, T.N. (1968). Receptive fields and functional architecture of monkey striate cortex. Journal of Physiology, 195, 215-243.

Julesz, B. (1984). Toward an axiomatic theory of preattentive vision. In G.M. Edelman, W.E. Gall and W.M. Cowan (Eds.). Dynamic aspects of neocortical function. Neuroscience Research Foundation.

Kahneman, D., & Treisman, A. (1984). Changing views of attention and automaticity. To appear in R. Parasuraman and J. Beatty (Eds.), Varieties of attention. New York, Academic Press,

Kanwisher, N. (1987). Repetition blindness: Type recognition without token individuation. Cognition, 27, 117-143.

Logan, G. (1988). Toward an instance theory of automatization. Psychological Review, 95(4), 492-527.

Marr, D. (1982). Vision: A computational investigation into the human representation and processing of visual information. San Francisco: W.H. Freeman & Co.

Nakayama, K. & Silverman, G. H. (1986). Serial and parallel encoding of visual feature conjunctions. Investigative Ophthalmology and Visual Science.

Nakayama, K., & Silverman, G.M. (1986). Serial and parallel processing of visual feature conjunctions. Nature, 320, 264-5.

Pylyshyn, Z.W. (1988). Here and there in the visual field. In Z.W. Pylyshyn (Ed.), Computational processes in human vision: An interdisciplinary perspective. Norwood, NJ: Ablex.

Pylyshyn, Z.W. & Storm, R.W. (1989). Tracking of multiple independent targets: Evidence for a parallel tracking mechanism. Spatial Vision. (in press).

Treisman, A. (1985). Preattentive processing in vision. Computer Vision, Graphics, and Image Processing. 31, 156-177.

Treisman, A. & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. Psychology Review, 95(1), 15-48.

Treisman, A., & Schmidt, N. (1982). Illusory conjunctions in the perception of objects. Cognitive Psychology, 14, 107-141.

Tulving, E., Schacter, D.L. & Stark, H. (1982). Priming effects of word-fragment completion are independent of recognition memory. Journal of Experimental Psychology: Learning, Memory and Cognition, 8, 336-442.

Von der Heydt, R., Peterhans, E. & Baumgartner, G. (1984). Illusory contours and cortical neuron responses. Science, 224, 1260-1262.

Figure 1

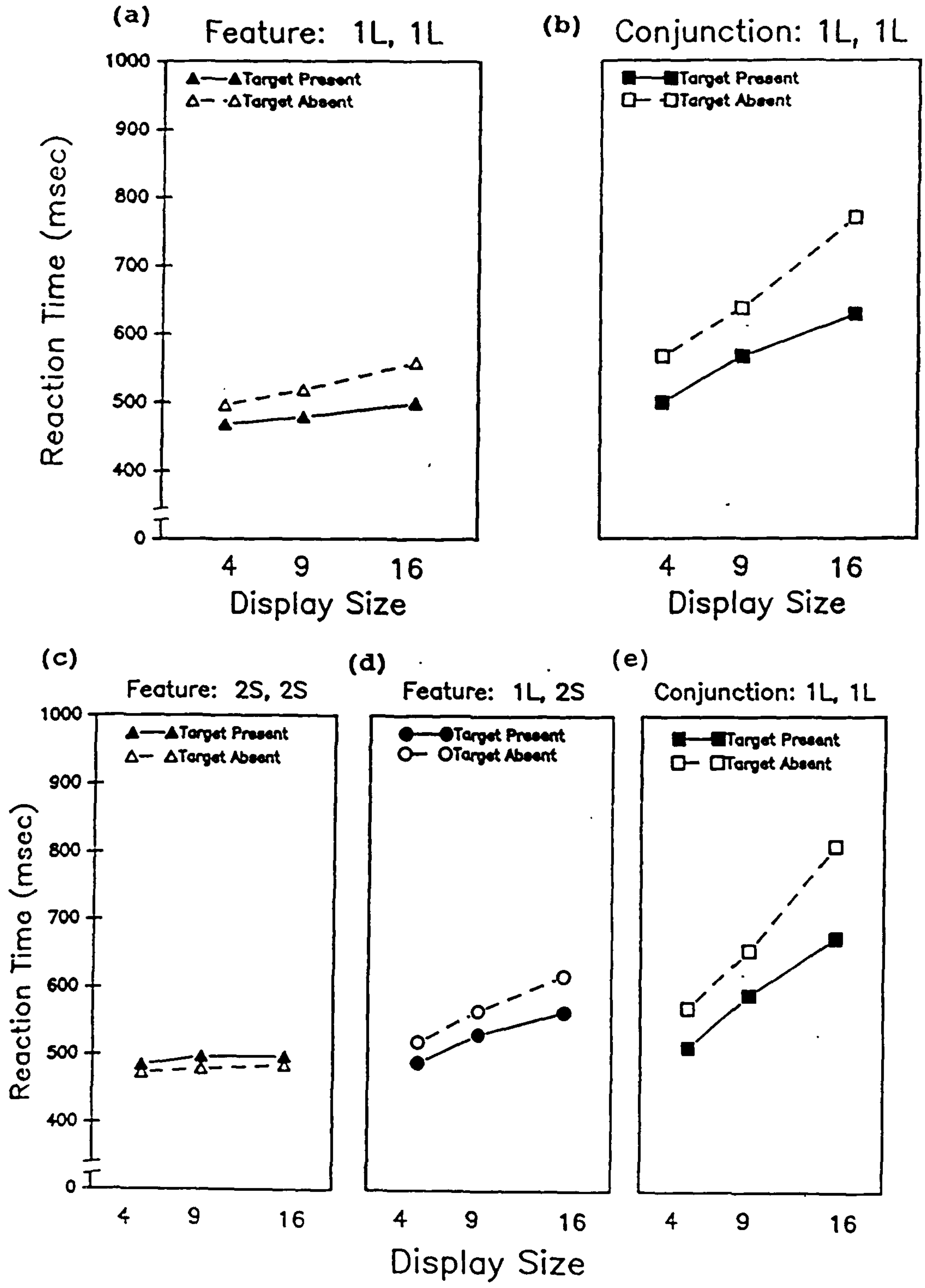
Schematic representation of the stimuli used to compare similarity effects in feature and conjunction search.

Color

	Red	Purple	Blue	Turquoise	Green
	11	12	13	14	15
	21	22	23	24	25
Orientation	31	32	Target 33	34	35
	41	42	43	44	45
	51	52	53	54	55

Figure 2

Mean search times for blue vertical target among different pairs of distractor elements.

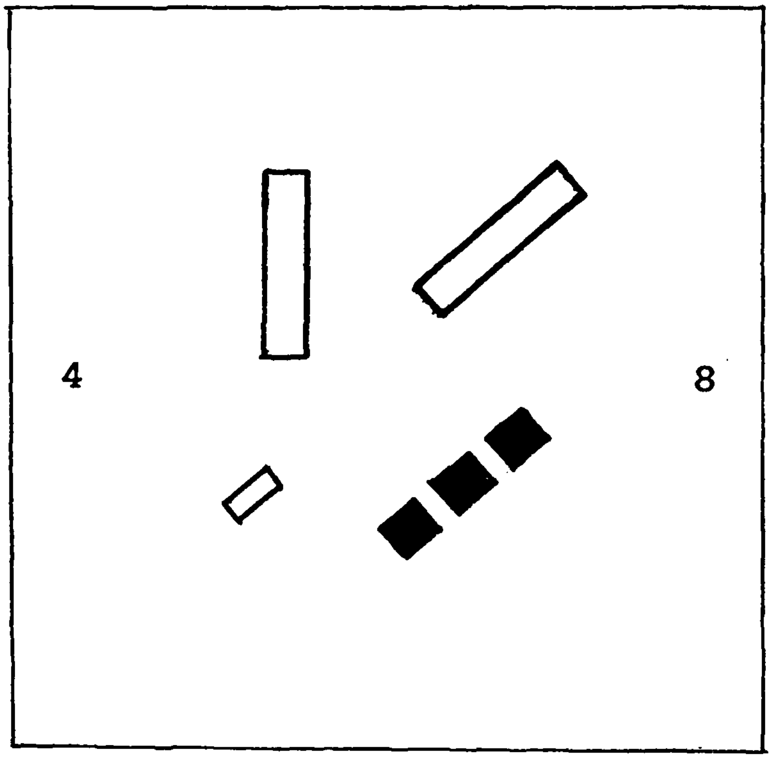


(a), (c) and (d) are different feature search conditions corresponding to conditions (1), (2) and (3) described in the text; (b) and (e) are the conjunction search condition. Figures (a) and (b) give results from one group of subjects, and (c), (d) and (e) from another.

Figure 3

Sample display to test the occurrence of illusory conjunctions.

Values not shown
(red, horizontal,
filled, medium-sized)



Conjunction Search Revisited

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Abstract

Search for targets defined by conjunctions of highly discriminable features can be very rapid or, in some cases, parallel. This paper explores three possible accounts based on (1) perceptual segregation, (2) conjunction detectors, and (3) inhibition controlled separately by one or more distractor features. Search rates for conjunctions of color, size, orientation and direction of motion bore no relation to predictions based on the physiology of single unit responses. Nor did they correlate at all closely with two independent measures of perceptual segregation with the same sets of stimuli. Each dimension appeared to contribute additively to conjunction search rates. The results could be accomodated by a modification of feature-integration theory, suggesting that spatial attention may be controlled by feature-based inhibition of distractor locations, as well as by a unitary, externally controlled attention window. Two further experiments gave evidence consistent with this hypothesis: Unknown targets were found only by serial search for each in turn, showing that conjunction distractors cannot be rejected in parallel even when highly discriminable. Search through four sets of distractors was more difficult than search through two; this favors the inhibition account rather than an alternative model assuming selective activation of target features.

Objects in the real world vary in a multitude of features, at least some of which appear to be coded by specialized, independent channels or modules in the perceptual system (see e.g. Braddick, Campbell and Atkinson, 1978; Graham, 1985; Livingstone and Hubel, 1987; Treisman, 1986 and Treisman and Gormican, 1988, for some reviews of the evidence). In order to perceive and identify the many thousands of objects we encounter each day, we must specify how these features should be integrated in the correct combinations and structural relations. If every possible conjunction had to be directly sensed by its own specialized detectors, there would quickly be a combinatorial explosion. Three general solutions seem possible: (1) A first solution would be to index the separate features present at any time by the locations they occupy and to scan these locations serially, conjoining the features currently attended (Milner, 1974; Minsky, 1961; Treisman, 1977; Treisman & Gormican, 1988); (2) A second solution would use differences in the latency of the neural information coming from different objects as they appear, disappear, move or change, and would conjoin features whose onsets coincide in time (Von der Malsburg, 1985) (3) A third solution (Pomerantz, Sager and Stoever, 1978) is to code at least some subset of possible conjunctions by directly sensing emergent features of their structure (e.g. closure for the three lines of a triangle; shape or area for the length and width of a rectangle). (4) In addition, there could be further special spatial attention atrategies that could be used to conjoin features in particular perceptual tasks. In this paper, we discuss two such strategies for visual search.

Treisman and Gormican (1988) and Treisman and Schmidt (1982) reported a variety of results consistent with the first hypothesis invoking spatial attention. Search for targets defined only by a conjunction of features gave linear functions relating latency to the number of items in the display, suggesting a serial check of each distractor in turn. When attention was divided, subjects reported many illusory conjunctions, recombining features from different objects present in the display. Perceptual grouping and boundary detection were difficult or impossible when the elements of the groups differed only in the ways they conjoined the same sets of features. Identification of conjunction targets appeared to be totally dependent on correct localization, whereas identification of feature targets could be correct even when they were mislocated in the display. Finally, more recently, Grabowecky and Treisman (in preparation; see Treisman, 1988, pages 213-214) found that the probability of correct report of conjunctions of features could be quite accurately predicted from the product of the probabilities of correctly reporting each of

their component features. This was true even at zero delay between the display and the cue indicating which item should be reported. Thus, there was no evidence for an initial wholistic perception followed by rapid decay of the conjunction information.

Most of these results were obtained with conjunctions of color and aspects of shape (curved vs. straight edges or vertical-horizontal vs. diagonal), but serial search, illusory conjunctions and failures of texture segregation have been shown also for parts of shapes (Julesz, 1986; Prinzmetal, 1981; Treisman & Gormican, 1988; Treisman & Paterson, 1984) and illusory conjunctions have been found for color, size, and outline vs. filled shape (Treisman & Schmidt, 1982).

The second account of the conjoining process - the temporal coincidence hypothesis - was recently tested by Keele, Cohen, Ivry, Liotti, and Yee (1988) who found no evidence that illusory conjunctions occur any more frequently for features whose presentation times coincide than for those that appear sequentially within 166 ms. On the other hand, features do appear to migrate between successive temporal intervals (Intraub, 1983; Lawrence, 1971) provided that they appear in the same location (McClean, Broadbent and Broadbent, 1982).

The third hypothesis, that some conjunctions are directly sensed by specialized detectors, in the same way as their component features, is consistent with physiological evidence that single units in most visual areas respond selectively on more than one physical dimension. Most cells in area V1, for example, are tuned both for spatial frequency and for orientation (De Valois, Yund and Hepler, 1982); many cells here and in prestriate areas are tuned to both a particular direction of motion and to a particular orientation or to both a color and an orientation (e.g. Thorell, De Valois and Albrecht, 1984; Desimone, Schein, Moran and Ungerleider, 1985; Maunsell and Van Essen, 1983). However, we cannot attribute to the whole organism the specialized sensitivities of any of its individual cells. The effective perceptual codes may be distributed patterns of activity across large populations of cells, and these could reflect separate dimensions rather than conjunctions of features. If we look at behavioral evidence, we find that the presence of a emergent feature like closure can mediate parallel search and can also prevent the formation of illusory conjunctions (Treisman & Paterson, 1984), offering some support for the third hypothesis as well as the first. However, the number of emergent features directly sensed by the visual system must be limited in order to avoid the combinatorial problem. When we looked for emergent features of pairs of oriented lines (such as intersection, juncture, convergence) using the parallel

search criterion, we found evidence for none (Treisman & Gormican, 1988).

The spatial attention hypothesis seemed, then, to offer the best general account of the data available. In the past two years, however, a number of investigators have reported exceptions to the claim that search for conjunction targets must be serial. Nakayama and Silverman (1986a) found that conjunctions of binocular disparity with color and with motion gave flat search functions relating latency to the number of elements. Conjunctions of color and motion, on the other hand, gave steeply increasing, linear slopes. The parallel conjunction of disparity with color or with motion could be explained by extending the spatial attention hypothesis to allow selection of a plane in depth (e.g. Downing & Pinker, 1984). The odd color or direction of motion would then pop out of the selected plane because of its unique value on that single dimension.

However, some further exceptions have since been discovered: Nakayama and Silverman (1986b) found parallel (or close to parallel) search functions for a different version of color-motion conjunctions, and for every combination of binocular disparity, spatial frequency, size, color and direction of contrast, provided that the two values on each dimension were highly discriminable (e.g. bright red and green patches, motion oscillating vertically vs. horizontally, black vs. white on a grey background). McLeod, Driver and Crisp (1988) found almost flat slopes for conjunctions of shape with direction of motion; Steinman (1987) found the same for conjunctions of binocular disparity with orientation and with Vernier offsets, and, after extended practice, for conjunctions of Vernier offset with orientation and lateral separation; Wolfe, Cave, and Franzel (1988) report completely flat functions for conjunctions of highly discriminable sizes, orientations (horizontal and vertical bars), shapes (plus and circle), and colors (red and green).

In addition, a finding by Pashler cast some doubt on the claim that search was serial and self-terminating when displays of fewer than eight items were used. Even though search latencies increased linearly with display size in his experiments, the slopes for negative and for positive trials were parallel rather than in the two-to-one ratio that we had previously found with larger displays. Pashler suggested that subjects might search groups of up to eight items in parallel, and that search became serial and self-terminating only across separate groups of about eight items at a time. The parallel slopes with small display sizes are not a universal finding: Parallel functions were found also by Houck and Hoffman (1985), but in other experiments (size-shape conjunctions in Quinlan and Humphreys, 1987; shape-color in Treisman and Gelade, 1980) there is little sign of

a break in the search function around display sizes of eight. It is not yet clear under what conditions one finds parallel slopes, but it will be important to clarify the controlling factors.

The finding of parallel search for conjunction targets appears inconsistent not only with feature integration theory (Treisman and Gelade, 1980) but also with the data from the other experimental paradigms that had initially prompted the theory. It therefore seems worth exploring carefully both the conditions that allow parallel detection of conjunction targets, and any accounts that could reconcile that result with the other findings described above. Prompted by Nakayama's initial reports, we began a series of experiments to replicate his results and to explore some possible interpretations with further experimental tests. In particular, we considered whether any alternative way of controlling attention to conjoin features might be available in the search task, but not more generally in perceptual identification.

We tested three possible strategies for conjunction search, each of which could be consistent with the previous more general account of spatial attention and feature integration. The first is that special grouping mechanisms might be invoked to segregate the two sets of distractors, allowing selective attention to one set and single feature search within the selected set (Nakayama, 1988; Steinman, 1987), as previously shown for spatially grouped distractors (Treisman, 1982). The second is that subjects might use a small number of conjunction detectors, available at preattentive levels of processing and activated by highly discriminable pairs of features. Likely candidates would be the feature pairs that activate single cells at early stages of visual coding. The third is that some pre-selection might be achieved by inhibition of distractor locations containing features that are inconsistent with the target.

Two of these hypotheses suggest new ways in which selective attention may modulate visual processing to allow the correct conjunctions of features to be formed. In feature integration theory, as it was previously formulated, the sequential processing of objects was achieved by a spatial scan of one location at a time. Figure 1 (from Treisman, 1988) illustrates how attention was used to ensure the correct conjunctions of features. The selection was controlled extrinsically by a spatial "spotlight" or "window" that could be narrowly focused or more diffusely spread (Eriksen and Hoffman, 1972; Treisman, 1982), but could normally not be spatially split (Posner, Snyder and Davidson, 1980). The selection was made within a "master-map" of locations, retrieving the features linked to the corresponding locations in a number of separable feature maps (Treisman, 1985; 1988). The alternative segregation

and feature inhibition strategies that we consider in this paper control selection through the same master-map of locations, but by inhibition or activation from one or more of the feature maps instead of from an externally controlled scan. A similar hypothesis has been proposed by Wolfe, Cave and Franzel (1988); we will discuss their results and a possible way of distinguishing their account from ours later in this paper.

The segregation hypothesis. We begin by considering the possibility that the parallel detection of conjunction targets in visual search depends on the ease of perceptual segregation between the two sets of distractor items. Many of the conjunctions that Nakayama tested included features related to phenomenological segregation in depth. Binocular disparity is the most obvious example, but stimuli differing in the direction of motion, and stimuli differing in size or spatial frequency also often appear to segregate into different planes. Both motion parallax and size gradients are useful cues to depth. If such perceptual segregation appeared salient, subjects might attend selectively to one of the two planes and do a parallel feature search within that plane for the other target-defining feature. For example, in a display of color-motion conjunctions, the items oscillating horizontally might segregate from those oscillating vertically. Within either plane, a target differing in color from the distractors should then "pop out" without any need for focused attention to each item in turn.

The feature-integration model can be modified to allow this optional strategy when the two sets of distractors differ in some highly discriminable feature (Treisman, 1988). The suggestion was that locations in the master-map might be selectively inhibited or activated not only by spatial attention acting directly on the master map, but also through their links to salient features in one or other feature map (see Figure 2). If attention could control selective inhibition of master-map locations from one or more feature maps, eliminating all the activity from locations that contained distractors with the inhibited feature, a parallel feature search across the remaining locations could be sufficient to detect the target. Whereas the inhibition extrinsically controlled by an attention spotlight or window seems to be restricted to a single area at a time (Posner, Snyder and Davidson, 1980), the inhibition controlled through a feature map could be directed to locations that are spatially interspersed with other non-inhibited locations. The effect of the inhibition would otherwise be the same in both cases: it would limit the set of features that are passed on together to be conjoined as parts or properties of the same perceptual object. Thus, for dimensions on which the two sets of

distractors differ sufficiently to produce non-overlapping distributions of activity in feature space, the constraints imposed by a unitary spatial attention window or spotlight would become irrelevant.

Note that this feature inhibition hypothesis need not be an ad hoc assumption solely conjured up to explain laboratory results from conjunction search tasks. It also provides a mechanism for figure-ground segregation, which is an essential task for early vision.

To avoid circularity, however, this account requires some independent measure of the extent to which particular displays allow attention to control the perceptual segregation of interspersed elements. Otherwise we would be inferring salient segregation from conjunction pop-out, and at the same time using it to explain conjunction pop-out, like explaining the effect of opium by its "dormitive power". In Experiments 1 and 2, we describe some attempts to find converging evidence for direct access to all the elements of one type through perceptual segregation, using displays in which we also test conjunction search. We propose two measures of global grouping and selective attention to an interspersed set of elements mixed with others in randomly ordered displays.

Experiment 1: Perceptual grouping and global shape recognition

The first index of segregation used the ease of access to the global shape of a perceptual group. The claim was that if subjects can selectively attend to one subset of distractors by inhibiting locations containing the other set, the boundaries of the selected set might be simultaneously available to mediate recognition of their global shape. Julesz (1971) showed that shape boundaries can be defined by the binocular disparity of the dots they contain, as well as by luminance or color discontinuities. Similarly, Cavanagh (1987) has shown that many aspects of shape can be carried by boundaries defined by differences in texture, motion and disparity. In most cases, however, the groups of elements were spatially contiguous or formed a good Gestalt (e.g. an annulus or outline cube). In the present experiment, we ask whether salient differences in features can mediate segregation and shape recognition for a randomly distributed set of elements interspersed with other irrelevant distractor elements. The subjects' task was to decide whether one set of four or five identical elements (in a 3 x 3 matrix) defined an area that matched a global grey pattern presented simultaneously beside them, or whether they differed from the grey pattern by one square, either added or deleted.

We tested six types of displays generated by conjoining pairs of values on each of four dimensions: color, size,

orientation and direction of motion. One obvious difference between Nakayama's results and our earlier tests of conjunction search was that the features he used were highly discriminable. We therefore used rectangular bars differing in pairs of values that were maximally discriminable on each of the four dimensions.

Figure 3 shows examples of these displays with elements differing in size and orientation, together with the corresponding grey shapes to be judged the same as or different from the area containing one set of elements. The prediction from the perceptual segregation account of conjunction search is that there should be a correlation across target types for each individual subject between the speed of matching the grey shape to the selected group of distractors and the speed of search for a conjunction target among the same sets of distractors.

Method

Stimuli. The displays were generated by an IBM AT with a Mitsubishi G479 color monitor and Artist 1 Plus color graphics board. The stimuli were oriented bars, either stationary or moving in one of two directions. They could differ along each of four dimensions: The colors we tested were pink and green (C.I.E. coordinates _____, luminance ____ and ____, against a white background, luminance_____); the sizes were $0{\cdot}5^0 \times 1{\cdot}6^0$ and $0{\cdot}3^0 \times 0{\cdot}9^0$; the orientations were 45^0 and 135^0, and the directions of motion were vertical and horizontal oscillation (over a distance of $0{\cdot}4^0$).

The four dimensions were paired to form six conjunction conditions: color/motion, size/motion, orientation/motion, color/size, color/orientation, and size/orientation. In the color/motion condition, for example, a display would contain either pink bars moving vertically mixed with green bars moving horizontally, or pink bars moving horizontally mixed with green bars moving vertically. The two dimensions not tested in any given condition were set at neutral values: these were grey for color (luminance ____), vertical for orientation, $0{\cdot}4^0 \times 1{\cdot}1^0$ for size, and stationary for motion. The six conditions were run in separate blocks.

In the conjunction search task, displays of four, nine and sixteen bars were used, randomly mixed within blocks. The two types of distractors in each condition were randomly placed in the cells of a square matrix, keeping density fixed and equating as closely as possible the number of distractors of each type. The largest matrix (4 x 4) subtended $8{\cdot}5^0$, at a viewing distance of 50 cm. The centers of the 2 x 2 and 3 x 3 matrices were randomly located within the larger 4 x 4 matrix, to equate the average distance of the stimuli from the initial central fixation point. In

half of the displays, one distractor was replaced by a target, which always shared one feature with each of the distractor elements. For example, with small green bars and large pink bars the target could be either a small pink or a large green bar. The location of the target was selected randomly on each trial. For each condition, all four combinations of the values on the two dimensions were tested as targets.

In the same-different matching task, two displays were presented side by side. On the left was a display of bars, identical to the 3 x 3 condition used in search on non-target trials. This display always contained nine elements (five of one type of distractor and four of the other), randomly positioned in a square matrix. On the left was a display consisting of connected solid gray squares (11 x 10 mm each), filling the squares in the matrix corresponding to those that contained the selected set of distractors. On "same" trials, the grey squares exactly matched the area occupied by the selected set; on "different" trials, one grey square was randomly added or deleted. Each display was 66 x 66 mm. The two displays were approximately 42 mm apart. Thus the total display was 174 x 66 mm (visual angle = 6.7^{0}).

<u>Procedure</u>. Subjects were tested on the conjunction search tasks in the first two sessions, and then in the same-different matching task in a third session.

In the conjunction search tasks, on each trial, the subject was asked to determine whether the display contained a target, and to press one key if a target was present and another key if it was not. The assignment of right and left hand keys was counterbalanced across subjects, but remained consistent across tasks for each individual subject.

A consistent mapping procedure was used: Each subject was assigned one feature from each of the four dimensions that would define his or her conjunction targets in all the different conditions. For instance, the first subject was assigned pink color, vertical motion, large size, and 45^{0} orientation. The targets for this subject were pink bars with vertical motion, large bars with vertical motion, large pink bars, pink bars tilted 45^{0}, and large bars tilted 45^{0}. Each value on each dimension was used equally often across the eight subjects and all combinations of values were tested, except that orientation was perfectly correlated with color. (Sixteen subjects would have been needed to test all possible combinations, and these two dimensions seemed least likely to generate an emergent feature). The order in which the six conditions were tested was counterbalanced across subjects.

A fixation point appeared 1.75 seconds before moving displays and subjects were given 8 seconds to respond. With stationary displays, the fixation appeared 1 second before,

and subjects had 5 seconds to respond. Feedback was given on incorrect responses. Subjects were tested in two sessions with three blocks of 48 trials in each condition in each session. The first of the three blocks was discarded each time as practice.

In the same-different matching task, subjects were tested with the same six types of stimuli. They were told that on each trial they would see two displays. On the left would be a display identical to the 3 x 3 displays they had seen in the previous experiment, except that there would be no targets. This display could be divided into two groups of elements. Subjects were instructed to attend to one group of elements and to try to notice the global shape formed by their boundaries with the other elements. They were then told to decide whether the global shape containing the selected elements exactly matched the formation of gray squares displayed on the right. If the two formations were identical, subjects pressed the right key; otherwise, they pressed the left key. They were instructed to respond as quickly as possible without making any errors. Subjects were shown examples of each of the six conditions and asked to select which type of distractors they wanted to match to the gray squares in each condition (e.g. pink moving vertically or green moving horizontally in the color-motion condition).

One second before each display, a fixation point appeared. Subjects were given up to 8 seconds to respond and received feedback on incorrect responses.

Subjects. Eight subjects (four men and four women) were tested. They were students at the University of California, Berkeley, who volunteered for the experiment and were paid $5 an hour for participation.

Results and Discussion

Table 1 gives the mean search times and the same-different matching times and error rates for each display type. We discuss first the search data.

Conjunction search. All the search functions have slopes that are significantly greater than zero ($p < .001$ in every case). The slopes are all quite linear with nearly all the variance due to display size contributing to the linear functions. There were consistent differences in the conjunction slopes for the different targets ($F(5,35) = 2.82$, $p < .05$) in an ANOVA on the slopes for each subject with each of the six conjunction targets. Some conjunctions were clearly more difficult to detect than others: size-color conjunctions were easiest and motion-orientation the most difficult.

The results are consistent with other recent findings suggesting that search for conjunction targets can be very

rapid. Although the mean slopes for conjunction targets in all six conditions were significantly greater than zero, the effects of display size were appreciably less than in the early experiments in which they ranged from about 40 ms to 100 ms per item on negative trials (Treisman & Gelade, 1980; Treisman, Sykes & Gelade, 1977). Three subjects in the present experiment had mean slopes for target present that averaged 10 ms or less across all six conditions, and seven of the eight subjects had at least one target for which the slope on target present trials was under 10 ms. For the eight subjects tested, the mean number of conditions with positive slopes under 10 ms was 2·6 out of 6.

We had previously shown a substantial effect on conjunction search rates of the discriminability of the component features (Treisman and Gelade, 1980, Experiment 2). In that experiment, we compared search for a more discriminable target (red O among green O's and red N's) with search for a less discriminable target (green T among green X's and blue T's). The slopes for the more discriminable targets were less than half those for the less discriminable ones (40 ms compared to 100 ms per item on negative trials). We attributed the reduction to a faster but still serial check of the discriminable distractors. This experiment used thin line drawings in colored ink on white cards in a tachistoscope. The present results with brighter filled bars in computer-generated displays take the discriminability effect further, and cast some doubt on the idea that search remains serial for each individual item in the display. We discuss the conjunction search results further in the context of Experiment 3.

<u>Same-different matching</u>. We turn now to the matching task. Here subjects showed reasonable accuracy in comparing the shape of the grey area to the global area enclosing one set of bar stimuli. The latencies varied significantly with the stimuli ($F(5,35) = 4.63$, $p < .01$), with size-color again the easiest and motion-orientation the hardest.

The main question raised in this experiment concerned the correlation between same-different matching times and the speed of conjunction search with the same displays. We looked at the correlations between the negative slopes and the "same" latencies. These seem to be the most appropriate trials within each paradigm to measure how well the two sets of distractors segregate, because they are not contaminated by the presence of a unique target or of a mismatching cell in the gray matrix. There was a positive correlation (0.74) across display types between the group mean negative slopes and the group mean "same" latencies. The correlations within individuals were, however, in most cases lower than the group mean. The eight individual subjects' correlations were as follows: -0·09, 0·06, 0·12, 0·26, 0·48, 0·58, 0·69, 0·74, giving a mean r of 0·40. Although all but one are

positive, none of these correlations individually reaches significance.

One reason for the relatively low correlations might be that the stimulus bars in the search displays filled only a small portion of each matrix square, whereas the grey patterns filled the squares completely. The actual sharp edges of the grey patterns had to be matched to subjective edges inferred from the midpoints separating adjacent elements in the search displays. The segregation of the bars could have created subjective boundaries that were rounded rather than rectilinear, or it could simply have isolated and grouped one set of the elements themselves without any of their background. In neither case would there be a close match to the presented grey pattern.

The fact that the correlations were all positive except one, and that some were quite high, encouraged us to try another measure of early preattentive grouping that might better predict the ease of search for conjunction targets.

Experiment 2: Apparent motion and perceptual segregation.

Apparent motion may offer another way to measure the ease of parallel access to a subgroup of items spatially interspersed among other distractors (Ramachandran, 1987; Treisman, 1986). The idea is to use the presence or absence of apparent motion when the subgroup in question is spatially shifted to and fro (relative to the distractors) between successive alternating displays (see Figure 4). If the group is available as a whole at the level at which apparent motion is detected, subjects should see global motion of the group, segregated from the background. In order to do this, they must establish the correspondence between the elements in the two displays, either in parallel or rapidly enough for all the elements to be paired off within the inter-display interval.

Since apparent motion is usually determined automatically, without conscious control, the correspondence problem is likely to be solved preattentively, if at all. The criteria for correspondence that are available to mediate apparent motion should therefore provide a new diagnostic for early visual processing. The aim was to see whether these criteria correlate with those for pop-out in conjunction search tasks. If so, we infer that they generate global groups of elements which can be selectively attended together, to the exclusion of other interspersed items.

Method

Stimuli. In each condition, two displays were presented successively, alternating within the same matrix of locations at a rate of 400 ms per cycle. Each cycle contained the following sequence: the first display was presented for 150 ms, followed by a blank screen for 50 ms; the second display was then presented for 150 ms and the screen was blank again for 50 ms. Each display consisted of 20 bars in a 5 column by 4 row matrix. The matrix of five columns by four rows subtended 12.6^0 by 10.5^0. Each cell subtended 2.6^0 by 2.5^0 and each stimulus bar was placed within its cell with its center at any one of four corners of an imaginary rectangle centered within the cell and subtending $1.1^0 \times 0.7^0$. One set of six elements (the targets) was presented in six randomly selected cells within the three center columns in one display, and was shifted either to the right or to the left in the next display.

In the coherent motion condition, all six elements moved one column either to the right or to the left, preserving their relative locations. In the incoherent motion condition, three of the target elements (randomly selected) moved coherently and the other three moved to new randomly selected locations within the three center columns plus one of the side columns. Thus on average, they also appeared to move in the same direction, but the group as a whole did not preserve its initial layout. The remaining 14 elements were slightly displaced within their original cells in the 5 x 4 matrix to a new randomly selected corner of the imaginary rectangle. The six targets on the other hand, were centered on the same point within their respective cells in the two displays.

The stimuli were the colored bars used in the previous experiment, except that some bar sizes were very slightly changed (from $1{\cdot}6^0$ to $1{\cdot}7^0$ and from $1{\cdot}1^0$ to $1{\cdot}3^0$ for the large and medium sizes respectively. This time, we tested only color, size and orientation; judging the apparent motion of elements defined by real motion seemed too confusing as a perceptual task.

Procedure. The task for subjects was to watch the alternating displays until they could decide whether the target group moved coherently or not. Coherent motion was defined as motion in which all six elements moved as a group in the same direction and across the same distance, preserving their relative positions within the group. The dependent measures were error rates and response times to decide whether the motion was coherent or not.

In the experimental conditions, each display consisted of two types of elements; for example, in condition CO, the displays contained either pink bars tilted right and green bars tilted left, or the reverse pairing. Each of the four types of elements for each pair of dimensions were used as targets, paired with the distractors that contrasted with

them on both dimensions. Two of the eight subjects were tested with each pairing of values on each pair of dimensions from the set containing color (pink and green), size (small and large), and orientation (45^0 and 135^0). For example, the first two subjects were given small green bars with large pink ones, small 45^0 bars with large 135^0 bars, and green 45^0 bars with green 135^0 bars. The next two subjects were given small pink bars with large green ones, small 45^0 bars with large 135^0, and pink 45^0 bars with pink 135^0 bars. The remaining four subjects were tested with the other two sets of combinations. As before, the dimension not tested in each condition was set at a neutral value (grey, medium-sized, vertical). Each of the two possible targets in each condition for each subject was tested, with the order counterbalanced within each pair of subjects.

Subjects were given an initial block of 48 trials in each condition with only the targets and no distractors, to familiarize them with the task and to make sure they understood the instructions. Each subject then ran another block of this control condition without distractors, to provide a baseline estimate of accuracy in conditions in which the correspondence problem could be solved without selectively matching the different features of subsets of elements. In the experimental condition, subjects were tested with the distractors present. They were given 24 trials with coherent and 24 trials with incoherent motion in each condition and with each target-distractor combination, after an initial 12 practice trials of each type with the distractors present.

Results

The mean accuracy is shown in Table 2 for each of the three display types. The control conditions show the accuracy with which subjects could discriminate "coherent" from "incoherent" apparent motion when only the relevant elements were present, and the embedded condition shows the accuracy when the distractor elements were also present. The difference can be taken as a measure of the efficiency with which the two sets of elements in a display could be segregated from each other and selectively matched to determine the global apparent motion of the group.

In every case except size-orientation with small targets, the grouping appears to have been quite effective. Thus, segregation on the basis of color and/or size for the larger size allowed almost perfect accuracy. For small targets, neither size nor orientation provided a good basis for judging global motion. Accuracy was only 70.8%, where chance would be 50%. The latency of decision was also much longer in this condition. There was no difference between large and small elements with color-size displays, but the

difference was significant with orientation-size displays ($F_{(1,7)} = 11.89$, $p = .011$). It seems that if the correspondence between the relevant items across displays could be made on the basis of either a shared color or a shared larger size, the apparent motion of the target group was detected without difficulty. However, if subjects were forced to detect the correspondence of the smaller items, by matching either their size or their orientation, they found it difficult or impossible.

The result does not conflict with claims that color differences are poor mediators of motion, whether apparent or real (Cavanagh, 1984; Livingstone and Hubel, 1987; Ramachandran & Gregory, 1978), since our stimuli were neither perfectly matched in luminance nor isoluminant with the white background. The colors were used not to define the boundaries of the elements with the background but to select which elements corresponded to which across successive displays. Pantle (1973) showed that, if the relevant displays were alternated with sharp transitions (as ours were), segregation of a group of red dots in motion against a background of green dots could be achieved.

Our main interest was in seeing whether the displays that give good global motion are the same as those that allow rapid or parallel search. The results do not in fact predict the search slopes very closely. Segregation for global motion seems to be determined by a single, highly discriminable feature, - either color, or size for the larger elements. If the same variables mediated selective attention to one subset of elements in the conjunction search displays, the ease of search should also depend primarily on the same two features, those that determined the segregation in the apparent motion task. Conjunctions of these features with any other feature should be detected about equally fast. (As we show in Experiment 3, each of the four features on its own allowed parallel detection). Instead, the results suggest that the difficulty of conjunction search was determined in each case by both the relevant dimensions.

The conjunction detector hypothesis. The second hypothesis we proposed to account for cases in which conjunction search is fast, or even independent of display size, was that there might exist a small number of specialized detectors coding pairs of values on particular pairs of dimensions as perceptual units. When these values were highly discriminable, subjects might use the presence or absence of activity in detectors for the target conjunction to determine their responses. To explore this possibility, we collected more data on the conjunction search tasks of Experiment 1.

Experiment 3: Comparison of conjunction and feature search with targets defined by color, size, orientation and motion.

This experiment had four aims: (1) to test more subjects in more sessions, in order to get more reliable data allowing detailed comparisons of search rates for different conjunctions of the same four dimensions. In this way, we could ask whether the ease or difficulty of conjunction search depends on the particular conjunctions tested, or only on one or other of the two features whose conjunction defines the targets. (2) We compared performance in search for conjunction targets with perfomance in search for targets defined by each of the same features on its own. (3) We tested whether with additional practice the search functions would become flatter or even completely independent of display size. (4) We looked at the effects of different spatial distributions of the distractors on one of the conjunction search tasks, as a final test of the perceptual segregation hypothesis.

Method

Stimuli. In the conjunction search conditions, the displays were identical to those used in Experiment 1, except that for eight of the ten subjects, the viewing distance was accidentally increased to 56 cm with a corresponding decrease of 12% in all the visual angles. For the feature search conditions, the distractors were homogeneous and differed from the target only on one of the four dimensions, with the other three dimensions set at the neutral value.

To test the effect of different spatial distributions, displays with motion-color conjunctions were used. In one condition, the display was spread over a larger area, with the distances between the bars increased by a factor of 1·5, keeping the bar size constant. In another condition, the two types of distractors were presented in the usual area but in a regular alternating checkerboard arrangement. In the third condition, constraints were placed on the number of distractors of the same type that could occur in adjacent squares as follows: Each 2 x 2 array within the larger displays contained either two instances of each type of distractor or two of one type, one of the other and the target.

Procedure. The procedure was the same as in the search tasks of Experiment 1, except that subjects were tested on the six conjunction search conditions in three one-hour sessions on separate days. Each session consisted of four blocks of 48 trials for each condition. These subjects were therefore tested in a total of 3456 trials, compared to those in Experiment 1 who received 1728 trials. The first session and the first block in each condition of the other two sessions was discarded as practice. The order of conditions was counterbalanced across subjects.

Ten subjects were tested, of whom eight were also tested in two further sessions with the targets defined by a single feature on each of the four dimensions, and with the three spatial variants of the motion-color conjunctions. The order of conditions within the single feature search and within the different spatial tests with color-motion conjunctions was counterbalanced across subjects.

Subjects. The ten subjects (four men and six women) were students at the University of California, Berkeley, who volunteered and were paid $5.00 an hour for participation.

Results and Discussion

The search functions in each condition are summarized in Table 3, which gives the mean slopes relating search time to display size, the intercepts, and the proportion of the variance with display size that can be accounted for by a linear function. Error rates averaged 6% or less at all display sizes in all conditions. The feature search conditions all gave very fast latencies and flat search functions, none of which departed significantly from zero slope with display size. Thus, the different values on all four dimensions were sufficiently discriminable to give parallel detection with the targets "popping out" of the displays.

As in Experiment 1, the slopes in the conjunction conditions were all significantly greater than zero ($p < .001$ in every case), and again linearity accounted for nearly all the variance due to display size. There were significant differences between the different conjunctions, both in mean search times ($F(5,45) = 25.10$, $p < .0001$) and in the interaction with display size ($F(10,90) = 2.85$, $p < .01$). The mean search times did not differ significantly for the subjects in the two experiments, but the search rates were faster than those in Experiment 1, probably because subjects in Experiment 3 had twice as many trials. An ANOVA showed significant interactions of experiment with display size ($F(2,32) = 5.08$, $p < .05$), with target type ($F(5,80) = 62.11$, $p < .0001$), and a three-way interaction with display size and positive vs. negative trials ($F(2,32) = 5.56$, $p < .01$). Within Experiment 3, there were also large individual differences in the mean search rates averaged across all six conditions (with a range from 7·1 to 31·0 ms per item, and there were differences between individuals in which conditions were most difficult.

The slope ratios averaged 0·57 across all display sizes for all conditions. Overall, we do not replicate Pashler's finding of parallel slopes up to display size 8. However, the color-size and the color-motion conditions did give Pashler's result in this experiment, and color-size also did so in Experiment 1. What might the controlling variables

be? There is a strong negative correlation of -0·85 between the slope ratio from displays of 4 to 9 and the overall mean of the positive and negative slopes for displays of 4 to 16. Thus, the easier and the more parallel the search, the larger the slope ratio for small display sizes. The slope ratios for small displays were also larger for the more practiced subjects of Experiment 3 than for those of Experiment 1. This would be consistent with the idea that as search becomes easier, subjects process larger and larger groups of items in parallel. Pashler's search rates were high, averaging about 25 ms per item for display sizes of 2 to 24. (However, Houck and Hoffman's were slower, averaging about 45 ms per item, despite the slope ratios of 1·0).

The main aim in this experiment was to get more reliable data to explore the conjunction detector hypothesis. The suggestion was that certain conjunctions of physical variables are detected directly by specialized cells in the visual system. Any prediction from the physiology of single unit responses would make conjunctions with orientation, (especially of spatial frequency and orientation), among the easiest, and conjunctions of color and motion among the most difficult. Most single units have both a preferred orientation tuning and a preferred spatial frequency or direction of motion. On the other hand, there is considerable evidence for functional segregation of color and motion between the parvo- and the magno-cellular pathways and between areas V4 and MT. The predictions of relative difficulty from the evidence for physiological "conjunction detectors" are not fulfilled, either by Nakayama and Silverman's data (1986b) or by those reported here. In fact, if anything, the reverse is the case, with conjunctions including orientation as one of the relevant features giving slower search than conjunctions of color and motion.

The results of this experiment also raise further problems for the segregation hypothesis. First, the conditions in which the spatial lay-out was varied showed almost no effects of spatial spread or of spatial grouping. The effect of arrangement was not significant, and the interaction between arrangement and display size was only marginally significant ($F(6,42) = 2.32$, $p = .051$), reflecting the slightly steeper slopes with the larger area and the slightly <u>flatter</u> slopes with the more intermixed condition, - the opposite of the effect expected from spatial grouping. Performance seemed to be almost independent of the regularity, density and mean size of homogeneous groups. This result certainly gives no support to the prediction from the segregation account that increased spatial heterogeneity might impair parallel access to subgroups of distractors.

Secondly, the segregation hypothesis assumes that attention can be directed to one set of items on the basis

of one of their features, presumably the more discriminable, and that within the attended subset a feature search on the other dimension should detect the target. Since all the feature searches were parallel when only one dimension was varied, this account predicts that search rates should depend primarily on the segregating dimension. If for example, color allowed good segregation and rapid search when paired with size, the same color segregation should be equally effective when paired with other dimensions. To check this possibility, we carried out a further analysis of the search results, pooling the data from the 8 subjects of Experiment 1 and the 10 from Experiment 3. Since the most salient feature could differ between individuals, we took each subject's flattest slope on trials with the target present. The mean slope was indeed very shallow (3·5 ms) and the target varied across individuals. The prediction would then be that one of the same two features that allowed this parallel detection in the fastest search condition should also determine search when conjoined with the other two features with which it was tested. These slopes with shared features would then be both flatter than the others and more similar to each other than they would be to the conditions which differed from them in both features. For example, if SC were the fastest condition for one individual, then the slopes on either SM and SD or CM and CO (or both) should also be shallower than those in MO. Moreover, the mean difference for that individaul between SO and SM or between CI and CM should be lower than the mean difference between SO and CM and between SM and CO. In fact, the mean slope for the faster pair of conjunctions with a shared feature was 10·7 ms/item; for the slower pair with the other shared feature it was 17·6 ms/item, and for the condition with no shared features it was 13·5 ms/item. The difference between 10·5 and 13·5 ms/item was just significant ($t(17) = 2.197$, $p < .05$), but the difference between the mean slopes with and without shared features was actually in the wrong direction (14·1 vs 13·5 ms/item. The mean differences between the two pairs of slopes with shared features and the two pairs with no shared features were almost identical (8·1 and 8·6 ms). The segregation hypothesis therefore gets little support from the individual subjects' data.

Unlike earlier experiments, this one controlled the discriminability of the individual features and varied only their conjunctions. It allows the new conclusion that no single feature determines the difficulty of the conjunction search tasks. Each feature gives a range of different search rates depending on which other feature it is paired with. Moreover, the difficulty of the conjunctions seems to be independent of the difficulty of each feature on its own. Orientation is the second fastes feature target, but it gives the slowest conjunction search performance.

Additivity of feature effects on conjunction slopes. The conjunction search results suggest, in fact, that the two features in each conjunction made additive contributions to the slopes of the search functions. The mean slopes for all 18 subjects (i.e. the negative slope plus twice the positive slope, divided by two) can be predicted to within less than 1 ms by the assumption that, when each was relevant, size contributed 6·5 ms, color 7·5 ms, motion 15 ms and orientation 21·5 ms to the average time required to process each item (see Table 4). A similar additivity holds for the results of Experiment 3 alone, (with estimated contributions of 4·5 ms for size, 7·0 ms for color, 13·0 for motion and 16·0 ms for orientation), except that the observed slope on movement-orientation conjunctions was too low by 4·6 ms. This was due entirely to one subject who gave aberrant results on positive trials in this condition, with a very high intercept (1200 ms) and a slope of -13 ms per item. For latencies on negative trials only, the additivity was almost perfect in Experiment 3, as it was for the mean of negative and positive trials excluding the one aberrant subject. The smaller estimates of the time contributed for each feature can probably be explained by the extra practice the subjects had in Experiment 3.

The apparent additivity of feature effects on the slopes puts constraints on possible interpretations of conjunction search. It is consistent with the idea that each feature is separately processed at some level before the target is found, and that both features play independent roles in locating the target or in determining its absence. However, note that the additive contributions cannot be predicted from the single feature search results. They must reflect some aspect of the conjunction process. The simplest account is that subjects must check all the elements in every display, rejecting each on the basis of whichever feature differentiates it from the target. They may check subgroups in parallel but they do not selectively search one type of distractors.

We cannot rule out the possibility that on any given trial, subjects used just one feature to control the search, but that they varied which feature they used from trial to trial. However, if they did so, the proportion of trials on which the subjects as a group used any given feature would have to be the same whatever the other feature with which it was conjoined, in order to preserve the overall additivity. This account seems more far-fetched than the alternative, that in general both features contributed to the slopes on every trial.

The result is surprising in the light of an experiment by Egeth, Virzi, and Garbart (1984). They showed that when only three items shared the target color in displays of

five, fifteen or twenty-five items, search times were about the same for all three display sizes. They inferred that in conjunction search tasks, subjects check serially through only one set of distractors (presumably the smaller set when the numbers are unequal) and not through the whole display. Our apparently additive effects on the search functions are inconsistent with this conclusion for displays with equal numbers of each distractor type. It is possible that different strategies are used for equally divided displays and for displays with small subsets of distinctive elements. Somewhere between Egeth et al.'s ratios of 4 or 8 to 1 and the ratio we used of 1 to 1, there would presumably be a switch in the strategy subjects adopt, from selectively checking a subset of items to checking the whole display.

A feature-inhibition hypothesis. Can these different strategies and the range of different search rates we observed be reconciled with the framework proposed to account for feature integration phenomena in the wider range of tasks outlined in the Introduction? The most obvious move is to extend the earlier suggestion (Treisman, 1988) that attention can use the feature maps to modulate the activity in the master map of locations. When the proportions of the different types of elements in the display are very unequal, the strategy may be, as suggested earlier, to inhibit the larger subset from the feature map which most clearly distinguishes the distractors from the target. The same process in perception of natural scenes could underlie the typical salience of small figures relative to their larger backgrounds. However, when the proportions of the different distractor elements are more equal, the strategy may be to inhibit both sets of distractors from each of the two feature maps on which they differ from the target (see Figure 5). If there is some additional cost to controlling inhibition from each additional feature map, there could be a trade-off between the number of items to be searched when only one set is inhibited and the number of feature maps controlling the inhibition when more than one set is inhibited. Consider, for example, a display containing a vertical red target among vertical green and horizontal red distractors. When there are very few red items, the best strategy may be to inhibit only locations containing green items and to search the remainder. But when there are equal numbers of red and green items, it may be more efficient to inhibit all the distractor locations as effectively as possible, using both color (green elements) and orientation (horizontal elements) to define the unwanted locations. The red vertical target will then be the sole survivor on the battlefield, or the least affected if the inhibition is only partially effective.

The range of slopes we and others now obtain in conjunction search tasks would reflect the degree to which

selective inhibition is possible for each of the two features involved. The efficiency of feature-based inhibition will determine the discriminability of the target from the two sets of distractor locations in the master-map in which attention selects the items to be conjoined.

We now need a model relating target-distractor discriminability to the rate of serial search. Treisman and Gormican (1988) describe several experiments on feature search with targets differing from the distractors on a single shared dimension but with varying levels of discriminability. In each case, the slope of the search function increased as the discriminability of the target decreased. Slopes could be anywhere in the range from completely flat to 200 ms or more per item. However, the average search function from many such experiments was linear and the slope ratio close to 0·5, suggesting serial self-terminating search in each case. Our hypothesis was that subjects move attention at a constant rate but process items in groups of two, three, four or more, pooling the activity at the feature level within the attended group. We suggested that the number of items receiving attention as a group would depend on the signal-to-noise ratio of the target within the group.

This hypothesis can be naturally extended to cover conjunction search when the relative activation of the target and the distractor locations is modulated by feature inhibition. When the inhibition of distractor locations is strong, fewer may remain above a threshold for checking, or more may be checked in parallel without risk of false positive responses. For example, if inhibition is easily generated from feature maps for relative size, distractor locations containing elements that differ in size from the target would be scanned or with a large aperture or spotlight. Distractors differing from the target in a feature, such as orientation, which generates only weak inhibition or none, will be scanned more slowly, with a smaller aperture. The rate of scanning each subset of distractors will be independent of the other subset, giving additive contributions to the slope for the display as a whole.

Wolfe, Cave and Franzel (1988) recently proposed a similar account of the flat functions they found in search for conjunctions of highly discriminable features. In their version of the model, the selection is made by activation from the feature maps responding to the features of the target rather than by inhibition from the feature maps responding to non-target features of the distractors. However, as they also point out, the two accounts are hard to distinguish empirically. Wolfe et al. report some additional empirical data which support either of these two hypotheses. (1) They confirmed the finding by Bergen and

Julesz (1983) that search for a T among L's (in four different orientations) remains serial, even for subjects who show parallel search with conjunctions of color, size and shape. This is consistent with the claim that parallel search depends on control from separate feature maps. T's and L's differ only in the spatial arrangement of the same two oriented lines; thus, neither line on its own can be used to distinguish the target from any distractor. (2) They confirmed an earlier finding by Quinlan and Humphreys (1987) that search for triple conjunction targets differing from each distractor in two of their features was faster than search for the same targets among distractors that differed from them only in a single feature. For example, a large red O was found more quickly among large green X's, small red X's and small green O's than among large red X's, large green O's and small red O's. Either activation or inhibition from each of two feature maps could converge on the target or distractor locations in the master map, increasing the relative activation of the target location more effectively than activation or inhibition from a single feature map.

We had independently also compared conjunction search with targets differing in either one or two features from the distractors, using the same set of features as in Experiments 1 to 3. The results complement those described by Quinlan & Humphreys and Wolfe et al. and also add a new observation.

Experiment 4: Search for triple conjunctions

We used the color, motion and orientation dimensions of Experiments 1 and 3, so that we could compare triple conjunctions differing in one and in two features with the earlier results of search for double conjunctions of the same three features.

Method

Stimuli. There are eight possible conjunction targets composed of the three binary dimensions, color, motion and orientation. Two sets of displays were generated for each of these eight targets: In one set the distractors were the three possible combinations of features that differed from the target on one dimension each, and in the other set they were the three possible combinations that differed from the target on two dimensions. The stimuli were otherwise identical to those in Experiment 1.

Procedure. Each of the eight subjects was tested in separate blocks with two different targets composed of complementary values on each dimension. For instance, the

first two subjects searched for a pink 45^0 target moving vertically and a green 135^0 target moving horizontally. For these two subjects in condition 1 (one feature different) the pink 45^0 target moving vertically was presented with pink 135^0 bars moving vertically, green 45^0 bars moving vertically and pink 45^0 bars moving horizontally; in condition 2 (two features different), it was presented with pink 135^0 bars moving horizontally, green 135^0 bars moving vertically, and green 45^0 bars moving horizontally. Each target was presented in each of the two conditions in counterbalanced order. Subjects were given two blocks of 48 trials on each target in each condition. As before, there were three display sizes 4, 9 and 16 items with density matched across all display sizes.

Results and Discussion

Missed targets averaged 2%, 3%, 3%, and 5%, 7%, 13% in the two feature and one feature different conditions respectively, and false positives averaged 1%, 1%, 1% and 5%, 2%, 4% in the corresponding conditions.

The mean search latencies are shown in Figure 6, together with the means from Experiments 1 and 3 for the three corresponding double conjunctions. There was a large reduction in slopes for the triple conjunction with two features different relative to the triple conjunction with one feature different (slopes of 11·6 and 27·7 ms per item for two features different compared to slopes of 47·2 and 80·6 ms per item on positive and negative trials for one feature different). An ANOVA comparing these two conditions showed significant effects of condition ($F(1,7) = 33.93$, $p < .001$), of display size ($F(2,14) = 32.01$, $p < .001$), and of the interaction ($F(2,14) = 20.87$ $p < .001$). Thus, the results replicated the earlier findings that triple conjunction targets are found more easily when they differ from the distractors in two features compared to one. The slopes we obtained with conjunctions of motion, color and orientation are remarkably similar to those obtained with conjunctions of shape, size and color by Quinlan and Humphreys (12 and 27 ms per item compared to their 12 and 29; 46 and 83 ms per item compared to their 37 and 83). On the other hand, in our experiment the triple conjunction with two features different did not differ significantly from the mean of the three double conjunction conditions (from Experiments 1 and 3).

The results are consistent with the hypothesis that distractor locations can be inhibited via the feature maps coding non-target features. If inhibition converges on distractor locations from two maps rather than one, the target locations should stand out more clearly and fewer distractors would need to be checked, or larger groups could

be checked in parallel. We found a much larger difference than Wolfe et al., presumably because the features we used were less discriminable than theirs.

Like Quinlan and Humphreys, we were able to compare search for triple conjunctions and search for the corresponding double conjunctions when both differed in one feature from the distractors. A between subjects comparison showed that the search times for triple conjunctions with one feature different were significantly slower than those for the double conjunctions ($F(1,24) = 23.88$, $p < .001$), as were the search rates (the interaction with display size gave $F(2,48) = 21.04$, $p < .001$). They were also slower than latencies in the slowest of the double conjunction conditions, movement with orientation; (the interaction of display size with condition MOC vs. MO gave $F(2,48) = 7.95$, $p < .001$). The error rates were also higher for the triple conjunction. The difference was unclear in Quinlan and Humphreys' experiment because of substantial differences in speed-error trade-offs. Our results suggest a cost either to the increased heterogeneity of the distractors, or to the increase in the number of target features to be conjoined. A number of explanations are possible: If feature inhibition is used to help the search, it may be more difficult to implement when three separate feature maps are involved than when only two are. Alternatively (or in addition), although the target differs from each distractor in one feature for both double and triple conjunctions, it also shares an additional relevant feature with them in the case of the triple conjunction. It is therefore more similar to them as well as equally different from them (Tversky, 1977).

The search rates were about the same for the double conjunctions and for the triple conjunction with two features different. The slopes did not differ significantly for the triple conjunction compared with any of the double conjunctions although the mean search <u>times</u> were much slower for the motion-orientation double conjunctions. (The main effect of conditions comparing motion-orientation double conjunctions with triple conjunctions with two features different gave $F(1,24) = 10.69$, $p = .003$). Note that the three sets of double conjunction stimuli are contained within these triple conjunction stimuli. Subjects could have used inhibition from the same two feature maps for the triple conjunctions as they did for any of the double conjunctions. Inhibition from two features would be enough to remove all the distractor activity when the triple conjunctions differed in two features each. Hence, there was no reason to expect a difference in search rates for the easier double conjunctions (color-motion and color-orientation). The longer latencies with the motion-orientation double conjunctions could reflect the fact that

they required inhibition from both of the least efficient features, motion and orientation, whereas the triple conjunctions did not; color together with one of the two would suffice.

Experiment 5: Inhibition or activation?

Our account so far has made one arbitrary choice where Wolfe el al. made another: we have couched the theory in terms of inhibition from feature maps characterizing the distractors, whereas they talked of activation from feature maps characterizing the target. Is there any way of distinguishing these two accounts? It seems that inhibition might become more difficult and costly the more different features are involved. This is one possible account of the greater difficulty of triple than of double conjunctions when both differ in one feature from the distractors. However, an equally plausible account could be given in terms of activation varying with the number of shared target features: Activation from two of the three target feature maps would spread into each distractor location with the triple conjunction targets, compared to one of two with the double conjunctions.

A better test may be to keep the target-distractor similarity constant, or even to make it oppose the prediction from inhibition. This might be achieved by varying the number of different distractor features <u>within</u> a dimension. We can compare search for a standard double conjunction target (such as a green bar at 27^0 from horizontal among distractor green bars at 63^0 and gray bars at 27^0) with search for the same double conjunction among the same two distractor types mixed with two others with different non-target values (for example, pink bars at 27^0 and green bars at 90^0). If search depends on activation of the target features, green and 27^0, it should be helped, if anything, when half of the similar distractors are replaced with others that differ <u>more</u> from the target values. On the other hand, if search depends on inhibition of locations containing non-target values, this could be more complex and costly to achieve when there are four different features to inhibit than when there are only two.

The next experiment explores this prediction. We chose the features to be used in the standard two-distractor conditions (grey and 63^0) to be clearly more similar to the 27^0 green target than the added features in the four distractor condition (90^0 and pink).

<u>Stimuli</u>. The displays were the same as the color-orientations displays in Experiment 1, with the following exceptions: The largest displays subtended $8{\cdot}7^0$ and the smallest $3{\cdot}4^0$, with stimulus bars subtending $0{\cdot}3^0$ x $1{\cdot}5^0$;

two new orientations were used - 27^0 and 63^0 from the horizontal; and the stimuli were presented on a black rather than a white background.

Procedure. The target was always a green bar oriented at 27^0 from the horizontal. In the two-feature condition, the distractors were green bars at 63^0 and grey bars at 27^0. In the four-feature condition, half the distractors were the same as these, and the other half were green bars at 90^0 (vertical) and pink bars at 27^0. There were, as usual, three display sizes, 4, 9, and 16, with density controlled. Subjects were given seven blocks of 48 trials in each of the two conditions in counterbalanced order in a single one-hour session. The first block in each condition was practice and was not included in the analysis.

Subjects. Four men and six women from the volunteer subject pool were tested.

Results and Discussion

The mean search latencies in each condition are shown in Figure 6. An ANOVA showed significant effects of condition ($F (1,9) = 22.31$, $p < .01$), of display size ($F (2,18) = 41.60$, $p < .001$), of positive versus negative trials ($F (1,9) = 19.89$, $p < .01$), and significant interactions of condition with display size ($F (2,18) = 17.65$, $p < .001$), and of positive versus negative trials with display size ($F (2,18) = 13.06$, $p < .001$). The slopes were 17·1 and 30·9 ms per item on positive and negative trials in Condition 1 with just two distractor types, and 23·3 and 40·7 ms per item in Condition 2 with four distractor types. Error rates were correlated with mean reaction times: Subjects missed 2, 3 and 5% targets with two distractor types and 3, 7 and 10 % targets with four distractor types.

The experiment was designed to test whether search is more likely to be facilitated by activation of locations containing target features or by inhibition of locations containing distractor features. If the relevant process were controlled by activating target features, the four feature displays should be searched at least as fast as the two-feature displays, given that the extra two features were clearly less similar to the target than the first two. If anything, performance should improve when half the original distractors were replaced by more discriminable ones, because their locations should receive less spreading activation from the target feature maps. In fact, performance was significantly worse with the four-feature displays, suggesting a process of active inhibition that was more difficult to implement when more different features

were involved.

A similar detrimental effect of distractor heterogeneity has previously been shown by Farmer and Taylor (1980), Bundesen and Pedersen (1983) and McIntyre, Fox and Neale (1970) among others. Farmer and Taylor (1980) and Bundesen and Pedersen (1983) varied the number of different distractor colors presented in search for a color target. However, they did not compare the effect of replacing some similar color distractors with some that differed more from the target in the same direction. Increasing heterogeneity was therefore confounded either with an increase in the number of potentially confusable colors or with an increase in the directions in color space in which a discrimination had to be made (Farmer and Taylor). McIntyre, Fox and Neale (1970) varied the similarity of distractor letters to target letters. Comparing across two of their experiments, we see that increasing heterogeneity by adding less similar letters (eg. O's or U's to a display containing a target F or T among distractor I's) led to a decrease in accuracy. The results are consistent with ours; they suggest that rejecting varied distractors is more difficult than rejecting homogeneous distractors, even when the latter are on average more similar to the target.

If heterogeneity impairs search by making feature-controlled inhibition more costly, it should only do so on dimensions that distinguish the distractors from the target. Treisman (1988) found that variation on irrelevant dimensions had little or no effect on search for feature-defined targets. It is unlikely, therefore, that distractor heterogeneity interferes with search simply because it creates additional boundaries or gradients that attract attention (Julesz, 1984).

The feature inhibition account suggests that selection is achieved by gating unwanted locations rather than facilitating wanted locations. A related result was obtained with auditory speech messages in a dichotic attention task (Treisman, 1964). Selective listening to a message on the right ear was impaired more by a message in the left ear and one in both ears than by two messages in both ears. Attention seems to "filter out" unwanted stimuli (Broadbent, 1958) or "to attenuate" their effects (Treisman, 1960) rather than to move one or more "spotlights" to selected items. The filter analogy suggests that in the absence of attention, all the features present in the scene are automatically registered and perhaps tend to form all their possible perceptual conjunctions. Attention, on this view, is needed to exclude irrelevant features from the level at which the representations of objects are assembled.

Experiment 6: Search for unkown conjunction targets

The account we have proposed defines a strategy for making a target salient in conjunction search tasks by means of inhibition controlled from separate distractor feature maps. An alternative account is that highly discriminable distractor conjunctions can be processed and rejected in parallel. If attention can filter out conjunctions that are known to be distractors, advance knowledge of the target might not be critical to perfromance provided that the distractors are well known. On the other hand, the feature inhibition strategy depends critically on the subject knowing which particular conjunction of features defines the target on any trial. When the definition of the target is unknown, it can be recognized only as being different from the distractors - an odd man out. In this case, search should revert either to a serial process through all the distractors, or to a series of trial-and-error tests of inhibition from different pairs of feature maps until the target emerges.

To explore these possibilities, we chose as the distractors for each subject a pair of maximally contrasting three-dimensional stimuli - for example, one subject might be given as distractors throughout the experiment the large pink vertical bars and the small green horizontal bars. For these two distractor types, there are six possible conjunction targets that recombine the same set of features in different ways. When the target can be any of the six, the strategy of inhibiting locations containing distractor features should be impossible to follow, at least in a single pass. Either of two alternative strategies for search could be used. One would be to reject each distractor as an incorrect conjunction of features; this should presumably require focused attention and serial processing. The other would be to apply feature inhibition successively from different pairs of distractor feature maps and to see, for each pair, if any location remains unaffected. Any uninhibited but filled location should contain the target. Thus, a series of "fishing expeditions" could be tried: for example, inhibit locations containing pink items and horizontal items and see if anything remains; if so, it must be a target, a large or small green vertical bar. If this attempt fails, try inhibiting green and large; if anything remains, it must be a target - a vertical or horizontal small pink bar. A minimum of three such passes will be necessary and sufficient to exhaust the possible targets. (The third in this example would inhibit small and vertical bars; if anything remains, it must be a target - a large pink or green horizontal bar.) However, if on each such pass each of the targets requires a serial check of the display, albeit with a coarse-grained window, it might be simpler and more economical to do a single, fine-grained, serial scan, item by item, to positively identify and reject as a non-target each of the two distractor conjunctions.

Method

<u>Stimuli</u>. The stimuli in this experiment were the usual rectangular bars, varying this time in size, color and orientation, with two values on each dimension, (sizes $0{\cdot}5^0$ x $1{\cdot}8^0$ and $0{\cdot}2^0$ x $1{\cdot}0^0$ when viewed at a distance of 50 cm; colors pink and green; orientations 45^0 and 135^0, background white). The displays contained 4, 9 or 16 items with density controlled, in matrices of $8{\cdot}7^0$ x $8{\cdot}7^0$ for the 16 elements and $3{\cdot}4^0$ x $3{\cdot}4^0$ for the 4 elements.

There are four possible pairs of maximally different distractors, and for each of these pairs there are six possible conjunction targets. Each differs in one feature from one distractor type and in two features from the other. These sets of eight stimuli were used in different combinations to generate the search displays described below.

<u>Procedure</u>. Each of the four possible pairs of distractors was allocated to two of the eight subjects. The distractors for any subject remained fixed throughout the experiment. In one condition, subjects looked for any of the six conjunction targets, - in other words, for something that was neither of the two distractor conjunctions. In each of two sessions, they were given one block of 72 trials for practice, followed by four test blocks of 72 trials each. In six other conditions, they were tested on each known target in turn. They were shown one of the six targets before each block began and were then tested for 72 trials with that target. The first twelve trials were discarded each time as practice. Subjects were tested in both conditions in counterbalanced order in each of two separate one-hour sessions.

<u>Subjects</u>. Seven women and one man from the subject pool were tested; they volunteered and were paid $5 an hour.

Results and Discussion

Figure 8 shows the mean search times in the known and unknown target conditions. There were large and significant differences between the two sets of means ($F(1,7) = 50.44$, $p < .001$) and in the interaction with display size ($F\ (2,14) = 15.95$, $p < .001$). Looking separately at the six different targets, however, we find that there were large differences between both the mean latencies and the search rates for the six targets. The targets differed significantly from each other ($F\ (5,35) = 43.68$, $p < .001$); the interaction wtih display size was also significant ($F\ (10,70) = 10.20$, $p <$

.001), indicating that the rates of search were different; finally, the three-way interaction with known vs. unknown target was also significant ($F(10,70) = 5.06$, $p < .001$), indicating that the differences between the search rates for different targets were much larger when the nature of the target was unknown.

We classified the targets for each subject according to the feature which differentiated each one from the more similar of the two distractor types. Table 6 shows for each target the mean slopes, intercepts, error rates and proportions of the variance with display size that were due to linearity.

We look first at search for the single, known targets. Targets that differed only in size from the small distractors (i.e. they were large) and targets that differed only in color from the large distractors were found essentially in parallel. Although the slopes differed significantly from zero, the means were under 6 ms on both positive and negative trials. Following the feature inhibition strategy, these two targets would emerge from the displays if inhibition were applied to locations containing the small size and the color of the large items. In this case, no serial check seems to have been required. Next fastest were the targets differing only in size from the large items and in color from the small items, and slowest were the targets differing in orientation from either the large or the small items. Experiments 1 and 2 suggested that orientation also contributes considerably more than color and size to the slope of the search functions. Presumably, inhibition is difficult or impossible to control from feature maps coding orientation.

We can now compare the conditions in which the target was unknown. The results can be summarized as follows: There was a considerable increase on average, both in the intercept of the search function and in the mean slopes when the subject did not know which target the display would contain. However, the increase was greater for some targets than for others; for some, there was little increase in slope, although all showed a large increase in intercept. If subjects had been able to reject the distractors in parallel on the basis of a specific <u>conjunction</u> of features, this would certainly have been a good strategy. The two distractor types for any subject were known and constant throughout the two sessions of the experiment. In fact, subjects seem not to have used this option, either with parallel inhibition or with a serial scan. If they had located the target by default as an item that was <u>not</u> one of the two familiar distractors, we should not have found any differences in search rates for the different unknown targets. At most, there could have been an intercept effect, relfecting differences in the discriminability of the target.

Instead, subjects may have used the fishing expedition strategy of inhibiting different feature values successively, and checking for each target in turn. If they inhibited pairs of features, the first values tested would allow two of the possible targets to emerge; the next pair would produce the next two targets, and the last pair would give either the final two targets or allow a negative response. This strategy makes predictions relating the slopes in the unknown target condition to those in the known condition. The simplest hypothesis is that a serial self-terminating check is made for each of the six targets at the same rate as in the known target condition. The slope for the first unknown target would then be the same as for the same target in the known condition; the slope for the second target would be the sum of the negative slope for the first in the known condition and the positive slope for the second; the slope for the third target would be the sum of the negative slopes for the first two targets and the positive slope for the third, and so on.

Different subjects might search for the targets in different orders, so we calculated the expected rates separately for each individual, taking the order of search in the unknown condition from a rank-ordering of the observed slopes for that subject in that condition. The first two columns in Table 6 show the mean observed slopes in the unknown target condition, rank-orderd for each subject separately, and the mean predicted slope, estimated by summing the corresponding slopes in his or her known target conditions.

The observed slopes match the predicted slopes quite well for the first four targets, but they are lower than the predicted slopes for the last two targets and for the negatives. This undershoot can be explained by the large numbers of missed targets in these conditions. With displays of 16 items, subjects missed 28% of targets that differed only in orientation from the nearest distractor. It is likely that subjects cut short the search on the later passes through the display before they had checked every item. Consistent with this hypothesis, the mean error reaction times were almost the same as the mean correct times within the same conditions (averaging 1121 compared to 1105 ms). If the search times do reflect premature termination on the more difficult trials, we can correct the observed slopes as follows: We assume that the proportion of the display which is actually serially searched is given by the proportion of detected targets on positive trials. The proportion is smaller on unknown than on known target trials, so we assume that subjects search fewer items on each pass through the display than they do when it is the only pass for a single known target.

We used the observed errors in the known and unknown conditions for each target type to correct the slopes, based

on the number of items actually searched. The percent detections at each display size were used to estimate the effective display size (the actual number searched in each condition). The ratio of the slopes for items actually searched in the two conditions was then calculated. For example, if subjects detected all the 4, 9 or 16 targets in the known condition, but only 90% of the targets on diplays of 4, 80% on diplays of 9 and 70% on diplays of 16 in the unknown target condition, we assume that they searched $\cdot 9 \times 4 = 3\cdot 6$, $\cdot 8 \times 9 = 7\cdot 2$, and $\cdot 7 \times 16 = 11\cdot 2$ items in the unknown condition, and all 4, 9 and 16 in the known condition. The ratio of the slopes would then be 0.63 (i.e. the regression of the number of items searched in the unknown condition on the number searched in the known condition). We correct the slopes from the known condition to predict the slopes in the unknown condition, taking the calculated ratio for each type of target. The corrected predictions are shown in the third column of Table 7. The fit is now quite close, with a correlation of .995 and no systematic differences between the observed and the predicted slopes.

General Discussion

The main findings in this series of experiments were as follows: (1) We confirmed the results of Nakayama and Silverman, (1986b), Wolfe et al. (1988) and others, showing that search for conjunction targets can be fast, and in some cases parallel, when the features are highly discriminable. In our data, conjunctions involving size gave the fastest search rates, those involving color were the next fastest, motion third and orientation typically quite slow. The rank order would, of course, change if the discriminability on any dimension were reduced. In addition, we found that each feature appears to make an additive contribution to the time required to scan the display, suggesting that when the distractors are equally divided, both sets may be checked. When one set is much smaller than the other, as in Egeth et al. (1984), a different, more selective strategy may be followed.

Search is much faster when two features rather than one distinguish each distractor from the target. However, when only one feature differs, a triple conjunction is harder to find than a double conjunction. It is also more difficult to find a conjunction target among four different types of distractors than among two, even when the extra two distractors are more discriminable from the target than those they replace. Distractor heterogeneity on the target-defining dimensions makes selection more difficult. This could also explain the slower search for the triple compared to the double conjunction, since there were three distractor

types for the triple conjunction and only two for the double conjunction. Finally, known targets are found more quickly on average than unknown targets. The unknown targets all showed an overall increase in latency (intercept effect); some showed little change in search rate (slope) whereas others showed a substantial increase, both in slope and in errors (missed targets). The search rates for the unknown targets could be predicted by summing a sequence of rates for the known targets, as if they were found through a serial check for each possible target in turn.

We considered three possible accounts of the data. The simplest was that certain conjunctions are directly coded in parallel by specialized detectors tuned to respond to particular combinations of values on different perceptual dimensions. This hypothesis raises several problems, however. The first is that the correspondence with physiological evidence is very weak: The conjunctions with orientation, for which there is the most physiological evidence of direct neural coding, are those that are hardest to detect in search tasks. This objection is not conclusive since the functional interpretation of neural single cell activity is still unknown.

A second problem for an account based on conjunction detectors is the fact that subjects are unable to find an unknown target by coding and rejecting the known distractor conjunctions in parallel, even when the two distractor types are highly discriminable and constant thoughout all the conditions in two sessions of search (as in Experiment 6). Another difficulty is that this account leaves unexplained all the findings in other paradigms that initially prompted the development of the feature integration model, many of which used highly discriminable features. We need an account which is consistent with the occurrence of illusory conjunctions, with the large advantage of precuing the target location for perception of conjunctions, and with the dependence of conjunction identification on accurate localization. Finally, the hypothesis of direct conjunction coding leaves unexplained the observed continuum of difficulty, both for conjunctions on different dimensions and for conjunctions on the same dimensions, but differing in the discriminability of the relevant values. There seems to be no clear dichotomy, such that some conjunctions are coded in parallel and some serially; instead we find a whole range of search rates, depending both on <u>which</u> dimensions are paired and on the discriminability of the values on each of those dimensions.

None of these objections rules out a direct coding hypothesis for some conjunctions of features. However, taken together with the constraints imposed by the potential combinatorial explosion, they suggest that it is worth considering alternative special strategies for finding

conjunction targets in visual search tasks, strategies that could be compatible with the original feature integration hypothesis.

We explored two such strategies - the segregation strategy and the feature inhibition strategy. Both share the assumption of the original feature integration theory, that perceived conjunctions are formed by sequentially linking separate features through a shared map of locations. Both suggest an additional way in which a conjunction target may be found without any parallel coding of the other conjunctions in the display. Like the original theory, both link feature integration to spatial attention. They differ from it and from each other only in the mechanism for controlling the spatial selection of potential targets.

The segregation account combines the idea proposed by Egeth, Virzi and Garbart (1984) that attention can be narrowed to exclude one set of distractors, with the idea that a parallel feature search within the remaining subset might then become possible (Treisman, 1982). We suggested that the attentional segregation could be achieved by inhibitory links between the feature map coding a salient non-target feature and the locations in the master-map that currently contained that feature.

We devised two experiments to test the role of perceptual segregation, using two independent measures of segregation. The aim was to see whether segregation was controlled by the same variables that allowed parallel search for conjunctions. The results (with our equally divided displays) gave little support to this hypothesis. For some subjects, the difficulty of global shape-matching was almost independent of the rate of conjunction search, although for others the correlation was higher. Apparent motion was controlled either by color or by the larger size, whether these were conjoined with each other or with oriention, whereas the rate of conjunction search depended in each case on both the relevant features. Thus, neither global shape-matching nor apparent motion appeared to predict the ease of conjunction search. The segregation strategy may, however, be used when one subset of display elements is much smaller than the other and when the features defining it are sufficiently salient, as in Egeth, Virzi and Garbart (1984).

Further inspection revealed an apparent additivity of feature effects on the conjunction search functions, suggesting that both features contribute independently contribution to the search latencies. The additivity is consistent with a third possible strategy for search, the feature inhibition strategy. This differs from the segregation strategy only in allowing inhibition from two or more separate feature maps onto the single master-map of locations. Rather than removing just one set of distractors

from the search process and searching the other set in parallel, feature inhibition could be generated from all the feature maps coding non-target features, thus reducing the activity in all distractor locations. At the extreme, with sufficiently distinct and separable features, it might completely eliminate all the activity generated in the master-map by distractor elements, allowing the target to "pop out" equally fast whatever the display size. When the features are less discriminable, the inhibition would be less effective and a serial scan, extrinsically controlled, would be required, either element by element or through pairs, triplets or larger groups of elements.

This model can generate a whole family of slopes for conjunctions whose component features differ in discriminability. The additivity of feature effects results from the fact that each type of distractor element contributes to the search latencies. For example, in a search for a small green target among small pink and large green distractors, half the distractors could be rejected by their color, taking 7·5 ms per item, and half by their size, taking 6·5 ms per item. The scan is made through the master-map of locations in which locations differ only in their level of activation. The order in which the locations are scanned must be independent of the features they contain, in order to give linear slopes with a two-to-one rtio of target absent ot target present trials. But the rate at which each is scanned will reflect the discriminability of the non-target feature it contains.

The feature-inhibition hypothesis is very similar to one proposed by Wolfe et al. (1988) and, in more general terms, to the two-stage model of Hoffman (1979). It is consistent with the evidence from Wolfe et al. that search for conjunctions of the same elements in different spatial arrangements is serial; in this task the distractors have no unique features not shared by the target, from which inhibition could be controlled. The hypothesis is also consistent with their finding, replicated in our experiment, that distractors differing from a triple conjunction target in two features are rejected more efficiently than distractors differing only in one. It predicts the difficulty of detecting an unknown conjunction target among two known sets of distractors. The large differences in the speed of detection for different unknown targets ruled out an account in terms of a serial scan identifying each distractor conjunction. Instead, the results suggest that separate features were inhibited in several successive passes, allowing the unknown targets to emerge at different points in the sequence.

Finally, the feature inhibition hypothesis makes a prediction that may differentiate it from the alternative feature activation version of the theory proposed by Wolfe

et al. Keeping the target features constant, we showed that search was impaired rather than helped when we replaced half the distractors by others differing from the target on the same two dimensions but to a greater degree. If the search strategy had been to pre-activate the features characterizing the target, the greater discriminability of the new distractors should, if anything, have reduced the interference they caused.

The advantage of this expanded account of conjunction search is that it is consistent with the general hypotheses about feature integration that emerged from converging results in a variety of other experimental paradigms. It allows a range of search rates, depending on the discriminability of the features. It allows the possibility that search could be exhaustive rather than self-terminating, if few enough locations remain active after the inhibition takes effect to allow a parallel check without risk of false positives, as suggested by Pashler (1987). The account is also consistent with evidence suggesting search through just one subset of elements when these constitute a sufficiently small proportion of the display (Egeth, Virzi and Garbart, 1984). It may be easier to search three items serially than to inhibit their locations. Finally, feature inhibition could subserve a more generally useful function in everyday perception - that of allowing figure-ground segregation and the concomitant emergence of boundaries to global groups of elements sharing common values on different perceptual dimensions.

REFERENCES

Bergen, J.R. & Julesz, B. (1983). Parallel versus serial processing in rapid pattern discrimination. Nature, 303, 696-698.

Braddick, O., Campbell, F.W., & Atkinson, J. (1978). Channels in vision: Basic aspects. In R. Held, H.W. Leibowitz, & H.L. Teuber (Eds.), Handbook of sensory physiology (Vol. 8). New York: Springer, 1978.

Broadbent, D.E. (1958). Perception and Communication. London: Pergamon Press, 1958.

Bundesen, C., & Pedersen, L.F. (1983). Color segregation and visual search. Perception & Psychophysics, 33, 487-493.

Cavanagh, P., Boeglin, J. & Favrean, O. (1985). Perception of motion in equiluminant kinematograms. Perception, 14, 151-162.

Cavanagh, P. (1987). Reconstructing the third dimension: Interactions between color, texture, motion, binocular disparity, and shape. Computer Vision, Graphics and Image Processing, 37, 171-195.

De Valois, R. L., Yund, E. W. & Hepler, N. (1982). The orientation and direction selectivity of cells in macaque visual cortex. Vision Research, 22, 531-544.

Desimone, R., Schein, S. J. Moran, J. & Ungerleider, L. G. (1985). Contour, color and shape analysis beyond the striate cortex. Visual Research, 25, 441-452.

Downing, C.J. & Pinker, S. (1985). The spatial structure of visual attention. In M.I.Posner & O.S.M. Marin (Eds.) Attention and Performance XI, (pp.171-187), Hillsdale, N.J.:Erlbaum

Egeth, H., Virzi, R.A., & Garbart, H. (1984). Searching for conjunctively defined targets. Journal of Experimental Psychology: Human Perception & Performance, 10, 32-39.

Eriksen, C.W.W., & Hoffman, J.E. (1972). Temporal and spatial characteristics of selective encoding from visual displays. Perception and Psychophysics, 12, 201-204.

Farmer, E.W., & Taylor, R.M. (1980). Visual search through color displays: Effects of target-background similarity

and background uniformity. Perception & Psychophysics, 27, 267-272.

Graham, N. (1985). Detection and identification of near-threshold visual patterns. Journal of the Optical Society of America, 2, 1468-1482.

Hoffman, J. E. (1979). A two-stage model of visual search. Perception and Psychophysics, 25, 319-327.

Hubel, D.H., & Wiesel, T.N. (1968). Receptive fields and functional architecture of monkey striate cortex. Journal of Physiology, 195, 215-243.

Intraub, H. (1985). Visual dissociation: An illusory conjunction of pictures and forms. Journal of Experimental Psychology: Human Perception and Performance, 11, 431-442.

Julesz, B. (1971). Foundations of Cyclopean Perception. Chicago. University of Chicago Press.

Julesz, B. (1984). Toward an axiomatic theory of preattentive vision. In G.M. Edelman, W.E. Gall, & W.M. Cowan (Eds.), Dynamic aspects of neocortical function. Neurosciences Research Foundation.

Julesz, B. (1986). Texton gradients: the texton theory revisited. Biological Cybernetics, 54, 464-469.

Keele, S. W., Cohen, A., Liotti, M., Ivry, R. & Yee, P. (1988). Tests of a temporal theory of attentional binding. Journal of Experimental Psychology: Human Perception and Performance, 14, 444-452.

Lawrence, D.H. (1971). Two studies of visual search for word targets with controlled rates of presentation. Perception & Psychophysics, 10, 85-89.

Livingstone, M. S. & Hubel, D. H. (1987). Psychological evidence for separate channels for the perception of form, color, movement and depth. Journal of Neuroscience, 7, 3416-3468.

Maunsell, J. H. R. & Van Essen, D. C. (1983). Functional properties of neurons in middle temporal visual area of the macaque monkey. I Selectivity for stimulus directions, speed and orientation. Journal of Neurophysiology, 49, 1127-1147.

McIntyre, C., Fox, R. & Neale, J. (1970). Effects of noise similarity and redundancy on the information processed

from brief visual displays. Perception and Psychophysics, 7, 328-332.

McLean, J. P., Broadbent, D. E. & Broadbent, M. H. P. (1982). Combining attributes in rapid serial visual presentation. Quarterly Journal of Experimental Psychology, 35(A), 171-186.

McLeod, P., Driver, J. & Crisp, J. (1988). Visual Search for a conjunction of movement and form is parallel. Nature (London), 332, 154-155.

Milner, P.M. (1974). A model for visual shape recognition. Psychological Review, 81, 521-535.

Minsky, M. (1961). Steps towards artificial intelligence. Proceedings of the Institute of Radio Engineers, 49, 8-30.

Nakayama, K. (1988). The iconic bottleneck and the tenuous link between early visual processing and perception. In C. Blakemore (Ed). Vision: Coding and efficiency. Cambridge University Press.

Nakayama, K. & Silverman, G. H. (1986a). Serial and parallel encoding of visual feature conjunctions. Investigative Ophthalmology and Visual Science.

Nakayama, K., & Silverman, G. H. (1986b). Serial and parallel processing of visual feature conjunctions. Nature, 320, 264-5.

Neisser, U. (1967). Cognitive Psychology. New York: Appleton Century Crofts.

Pantle, A.J. (1973). Stroboscopic movement based upon global information in successively presented visual patterns. Journal of the Optical Society of America, 63, 1280A.

Pashler, H. (1987). Detecting conjunctions of color and form: Reassessing the serial serch hypothesis. Perception and Psychophysics, 41, 191-201.

Pomerantz, J.R., Sager, L.C., & Stoever, R.G. (1977). Perception of wholes and their component parts: Some configural superiority effects. Journal of Experimental Psychology: Human Perception and Performance, 3, 422-435.

Posner, M.I., Davidson, B.J., & Snyder, C.R.R. (1980). Attention and the detection of signals. Journal of Experimental Psychology: General, 109, 160-174.

Prinzmetal, W. (1981). Principles of feature integration in visual perception. Perception & Psychophysics, 30, 330-340.

Quinlan, P.T., & Humphreys, G.W. (1987). Visual search for targets defined by combination of color, shape and size: An examination of the task constraints on feature and conjunction searches. Perception & Psychophysics, 41, 455-472.

Ramachandran, V. (1987). Paper presented to conference on Neurophysiological Badenweiler, Germany, June 1987.

Ramachandran, V.S., & Gregory, R.L. (1978). Does colour provide an input to human motion perception? Nature, 275, 55-56.

Steinman, S.B. (1987). Serial and parallel search in pattern vision. Perception, 16, 389-399.

Thorell, L. G., De Valois, R. & Albrecht, D, G. (1984). Spatial mapping of monkey V, cells with pure color and luminance stimuli. Vision Research, 24, 751-769.

Treisman, A.M. (1960). Contextual cues in selective listening. Quarterly Journal of Experimental Psychology, 12, 242-248.

Treisman, A.M. (1964). The effect of irrelevant material on the efficiency of selective listening. The American Journal of Psychology, 77(4), 533-546.

Treisman, A. (1977). Focused attention in the perception and retrieval of multidimensional stimuli. Perception and Psychophysics, 22, 1-11.

Treisman, A.M. (1982). Perceptual grouping and attention in visual search for features and for objects. Journal of Experimental Psychology: Human Perception and Performance, 8, 194-214.

Treisman, A. (1985). Preattentive processing in vision. Computer Vision, Graphics, and Image Processing, 31, 156-177.

Treisman, A. (1986). Properties, parts and objects. In K. Boff, L. Kaufman and J. Thomans (Eds). Cognitive processes and performance, Chapter 35, pp. 1 - 70. Handbook of Perception and Human Performance, Vol. 2. NY, Wiley.

Treisman, A. (1988). Features and objects: The Fourteenth Bartlett Memorial Lecture. Quarterly Journal of Experimental Psychology, 40A, 201-237

Treisman, A., & Gelade, G. (1980). A feature integration theory of attention. Cognitive Psychology, 12, 97-136.

Treisman, A. & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. Psychology Review, 95(1), 15-48.

Treisman, A., & Paterson, R. (1984). Emergent features, attention and object perception. Journal of Experimental Psychology: Human Perception and Performance, 10, 12-31.

Treisman, A., & Schmidt, N. (1982). Illusory conjunctions in the perception of objects. Cognitive Psychology, 14, 107-141.

Treisman, A., & Souther, J. (1985). Search asymmetry: A diagnostic for preattentive processing of separable features. Journal of Experimental Psychology: General, 114, 285-310.

Treisman, A., Sykes, M., & Gelade, G. (1977). Selective attention and stimulus integration. In S. Dornic (Ed.), Attention and performance, VI. Hillsdale, N.J.: Lawrence Erlbaum,

Tversky, A. (1977). Features of similarity. Psychological Review, 84, 327-352.

Von de Malsburg, C. (1985). A mechanism for invariant pattern recognition. Presenterd at a conference on visual attention and action. Bielefeld, Germany, July 1985.

Wolfe, J. M., Cave, K. R. & Franzel, S. L. (1988). A modified feature integration model for visual search. Journal of Experimental Psychology: Human Perception and Performance (in press).

Table 1

Mean slopes of search functions and percent of variance with display size that is due to linear component; mean matching times and errors in the same-different matching task.

Stimulus displays	Search functions		Matching times		Matching errors%			
	Pos.	%Linear	Neg.	%Linear	Same	Diff.	Same	Diff.
Size-Color	10.2	99.5	17.3	96.1	1205	1259	3.2	5.0
Size-Motion	11.7	98.9	30.2	100.0	1354	1341	3.0	7.1
Size-Orientation	17.4	96.8	35.2	100.0	1365	1329	5.8	4.3
Color-Motion	11.0	93.0	23.6	99.9	1357	1299	2.0	6.6
Color-Orientation	18.4	99.8	37.0	99.8	1241	1349	1.8	9.0
Motion-Orientation	20.5	93.6	61.4	99.8	1477	1438	5.1	5.0

Table 2

Accuracy of judging coherent motion of groups of elements defined by color, size and orientation differences, and mean.

Display type	% Correct Embedded	% Correct Control	Difference	Search rates (from Expt. 1) Increase in latency(ms)	Search rates (from Expt. 1) Mean search rates (0.5 (Neg. + 2 Pos)
Color-Size	90.8	97.3	6.5	33	19.4
Color-Orientation	91.5	97.1	5.6	62	36.9
Size-Orientation					
Large targets	92.5	98.0	5.5	117	20.2
Small targets	70.8	96.8	26.0	982	50.0

Table 3

Mean slopes, intercepts and percent of variance with number of distractors that is due to linear component.

Conjunctions	Target Present			Target Absent		
	Slope	Intercept	%Linear	Slope	Intercept	%Linear
Size-Color	6.8	432	99.3	8.0	487	96.0
Size-Motion	9.0	580	100.0	16.1	607	99.3
Size-Orientation	10.9	536	99.4	21.0	517	100.0
Color-Motion	11.8	566	96.9	17.7	576	98.4
Color-Orientation	11.7	533	99.5	23.5	480	99.4
Motion- Orientation	9.5	884	95.5	29.5	839	99.9
Simple features						
Size alone	1.6	400	82.6	0.2	411	17.2
Color alone	0.8	356	41.7	-1.3	397	99.1
Motion alone	-1.4	508	45.8	0.2	498	11.0
Orientation alone	0.2	393	26.7	0.3	420	8.5
Spatial variants of color-motion displays						
Standard (session 3)	9.9	521	99.9	13.4	548	99.9
Larger Area	11.7	491	100.0	13.3	508	97.3
Checkerboard	9.9	478	95.4	11.0	513	96.5
Interspersed	9.0	521	92.6	8.6	561	99.1

Table 4

Mean slopes for each conjunction target, together with predicted slopes assuming additive contributions from each feature separately (shown in parentheses).

Experiment 1

	Color		Size		Motion	
Size	14.4	(14.0)				
Motion	21.7	(22.5)	21.4	(21.5)		
Orientation	29.5	(29.0)	27.5	(28.0)	36.4	(36.5)

Contributions

Size	6.5
Color	7.5
Motion	15.0
Orientation	21.5

Table 5

Mean slopes, intercepts and linearity (proportion of variance with display size that can be attributed to a linear function) for the various conditions of Experiment 6.

Feature differentiating target from most similar distractor		Known target Slope	Intercept	%Linear	%Errors
Large size	Pos.	2.9	394	97.9	2
	Neg.	3.9	461	92.2	2
Color for large target	Pos.	3.8	374	98.6	2
	Neg.	4.0	452	99.1	2
Small size	Pos.	8.4	387	98.0	4
	Neg.	13.6	415	99.0	1
Color for small target	Pos.	6.9	403	99.3	2
	Neg.	12.3	428	99.4	2
Orientation for large target	Pos.	5.5	487	99.9	4
	Neg.	11.8	484	98.3	4
Orientation for large target	Pos.	16.6	494	99.0	5
	Neg.	25.1	463	99.8	4
Mean	Pos.	7.4	423	99.9	3
	Neg.	11.8	451	99.8	3

Unknown target

		Slope	Intercept	%Linear	%Errors
Large size	Pos.	10.5	607	99.6	3
Color for large target	Pos.	11.2	638	99.1	4
Small Size	Pos.	12.5	609	78.9	6
Color for small target	Pos.	22.7	533	95.1	4
Orientation for large target	Pos.	34.6	695	99.5	17
Orientation small target	Pos.	53.6	648	98.6	26
Mean	Pos.	24.2	622	99.6	10
	Neg.	60.9	475	94.8	4

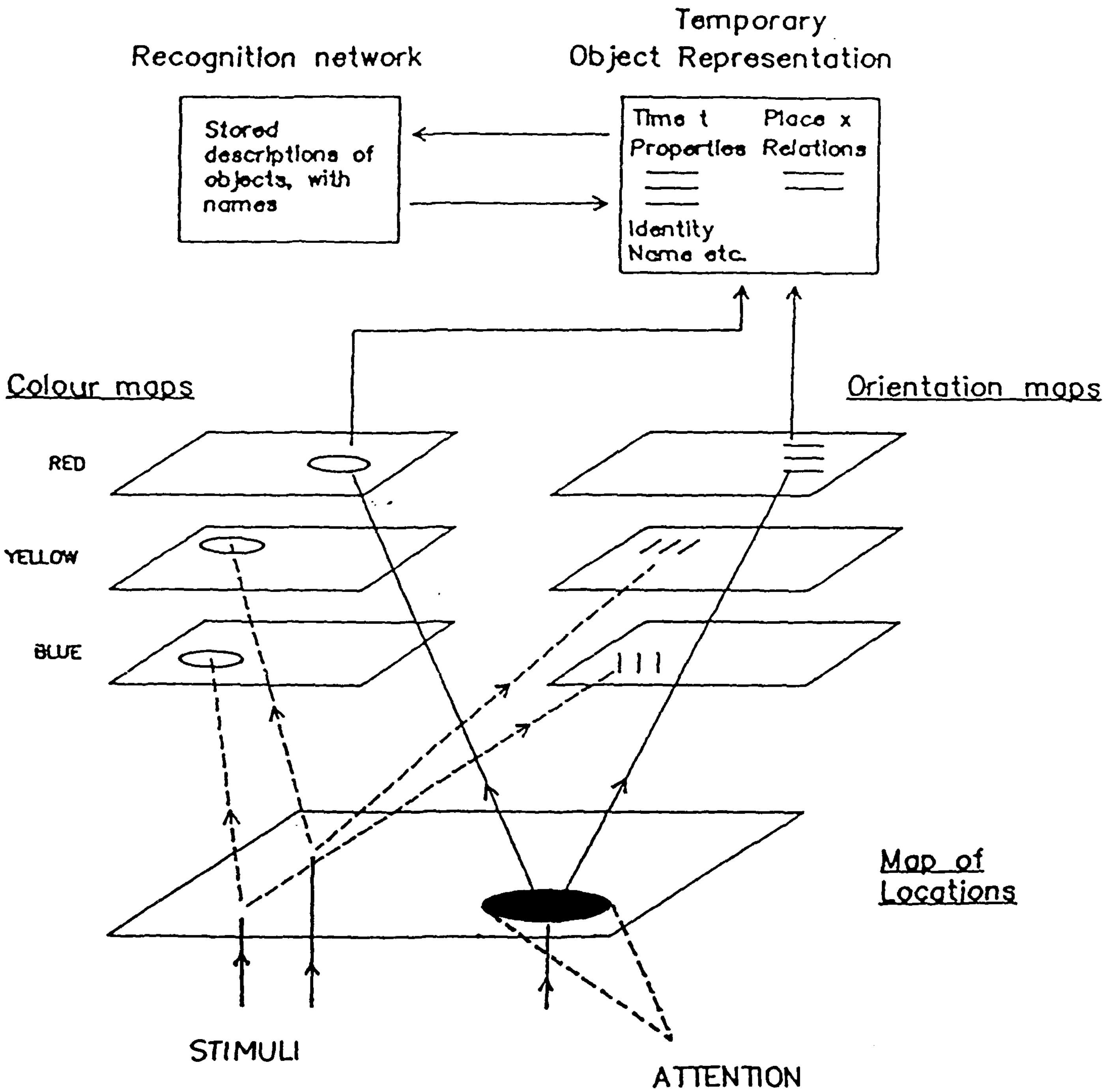
Table 6

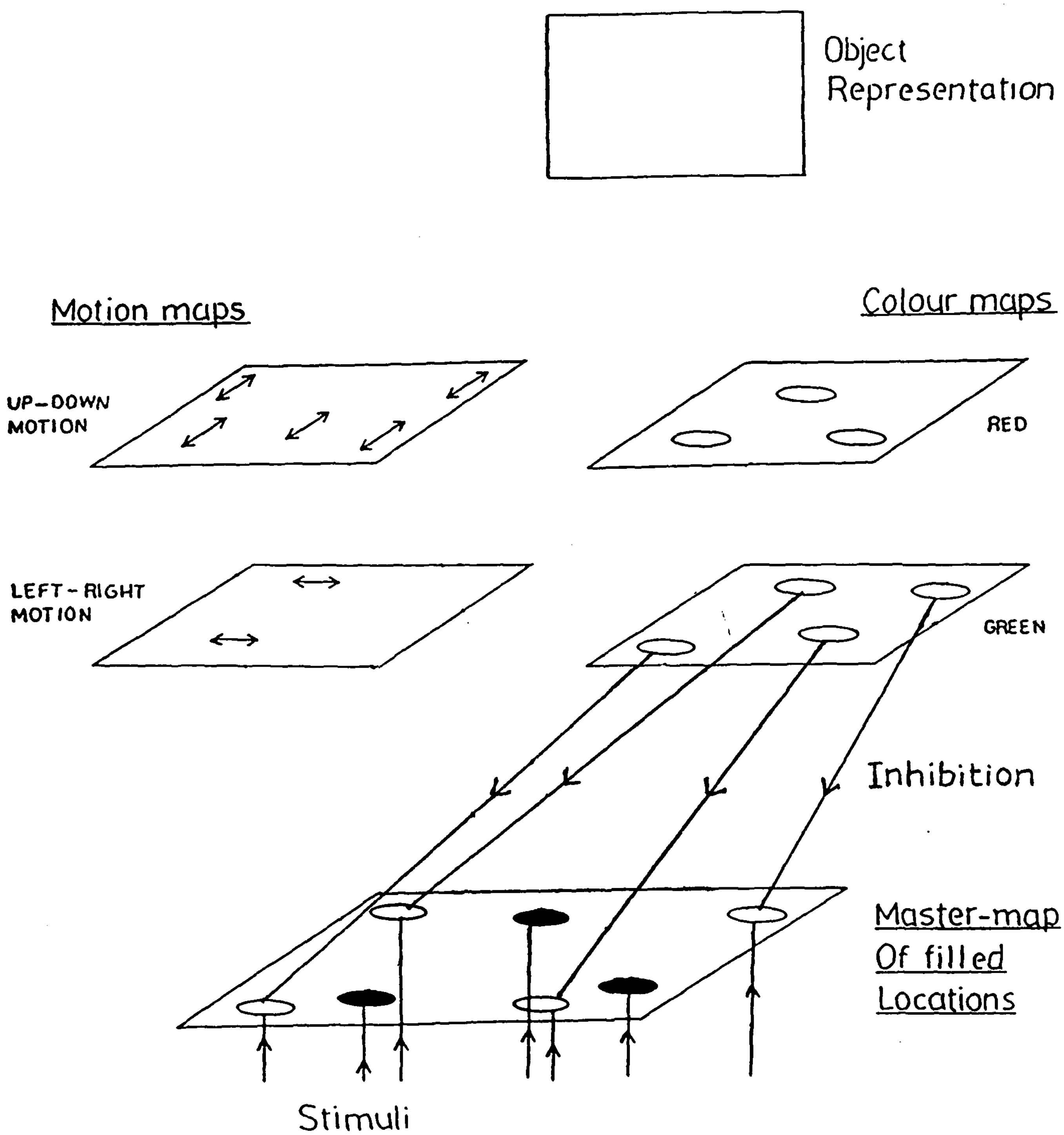
Mean observed and predicted slopes in the unknown target condition.

The observed slopes are rank-ordered for each subject separately.

	Observed	Predicted	Predictions corrected for errors
Positive trials:	5.3	4.5	4.1
	9.7	10.3	9.7
	15.9	19.1	18.3
	23.0	25.7	24.4
	35.5	42.2	37.8
	55.6	61.1	51.5
Negative trials:	60.8	70.4	58.1

Figures


Temporary
Object Representation
Recognition network
Stored descriptions of objects, with names
Time t
Place x
Properties
Relations
Identity
Name etc.
Colour maps
Orientation maps
RED
YELLOW
BLUE
Map of
Locations
STIMULI
ATTENTION

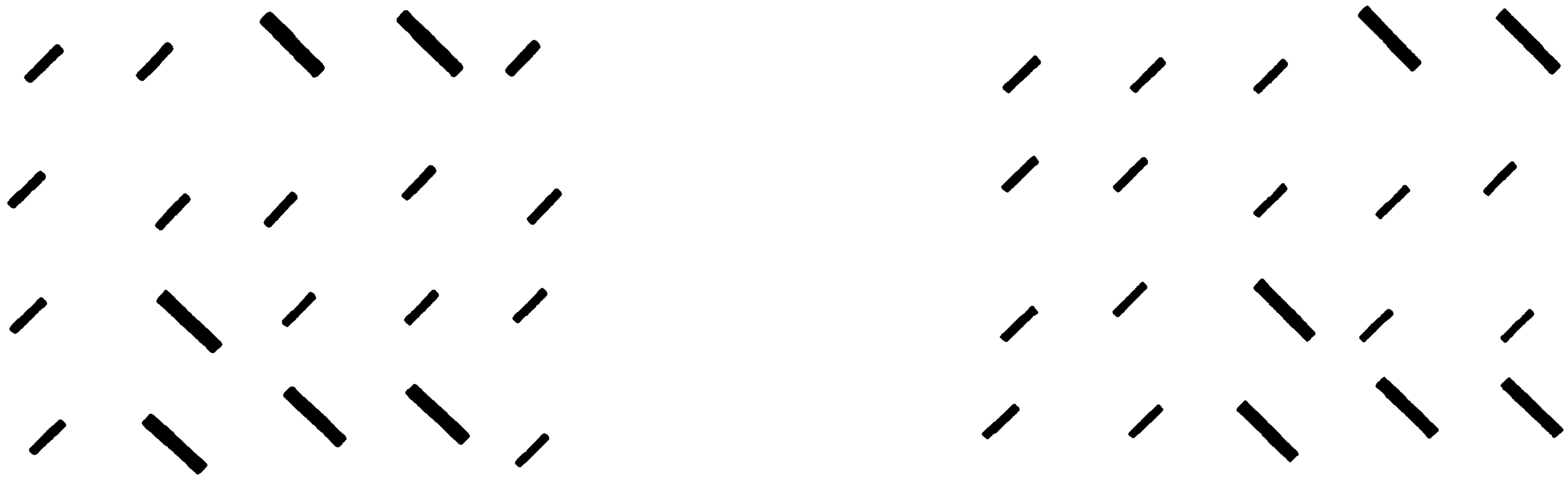


Object
Representation
Motion maps
Colour maps
UP-DOWN
MOTION
RED
LEFT-RIGHT
MOTION
GREEN
Inhibition
Master-map
Of filled
Locations
Stimuli

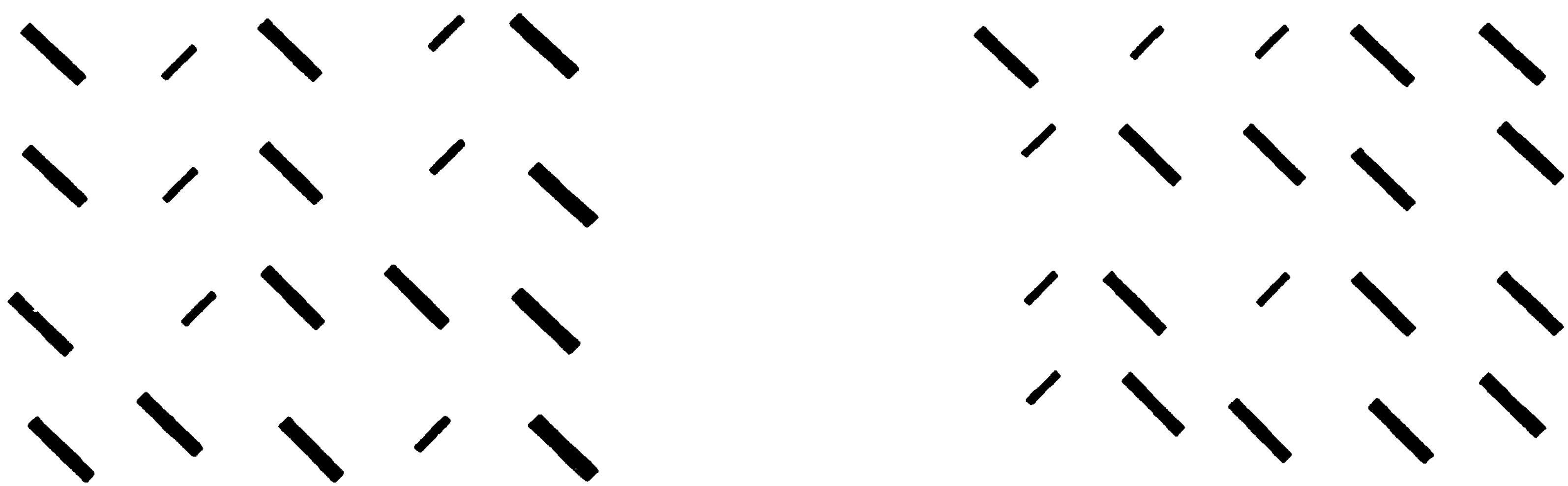
a)

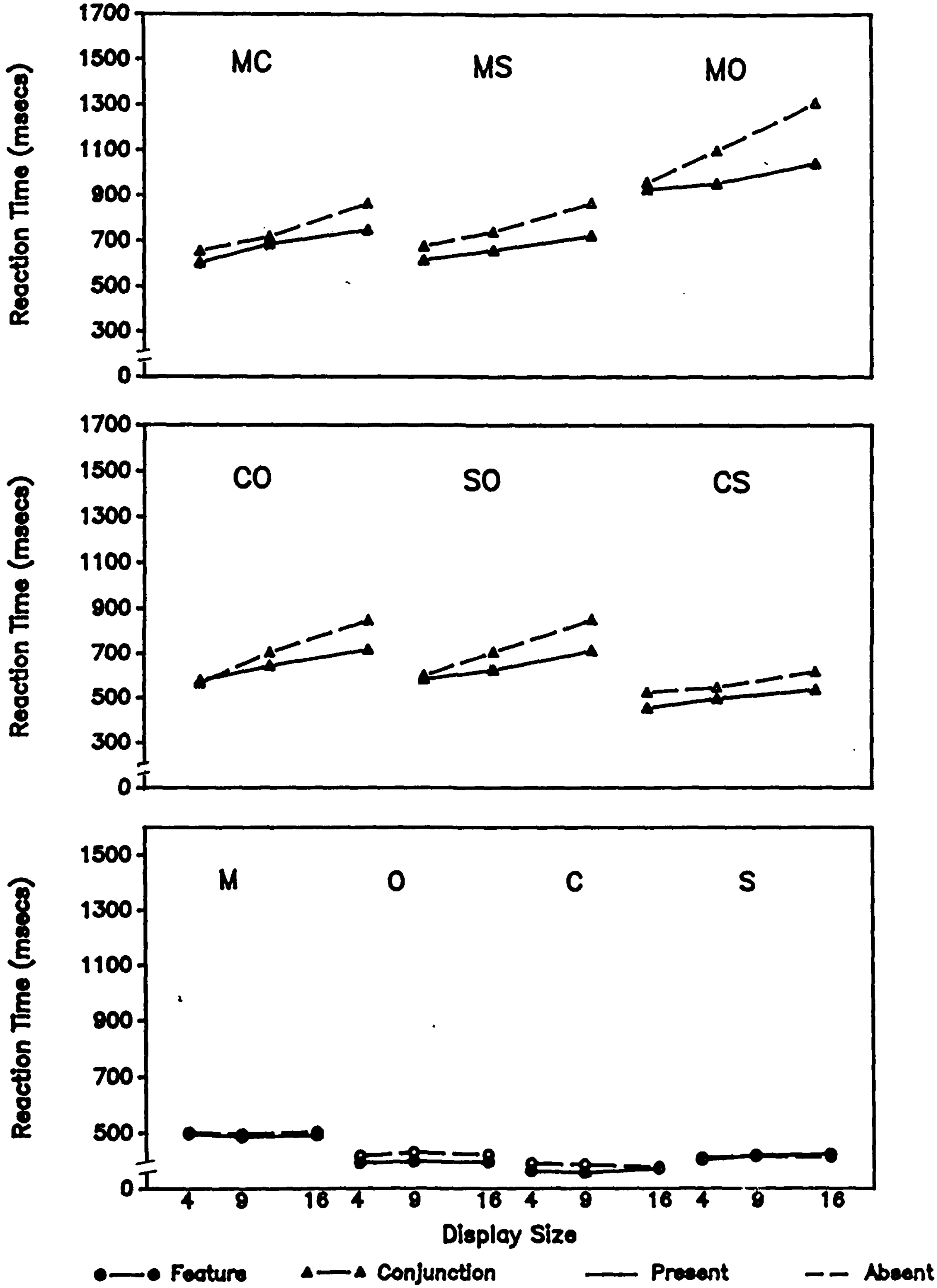
b)

a)

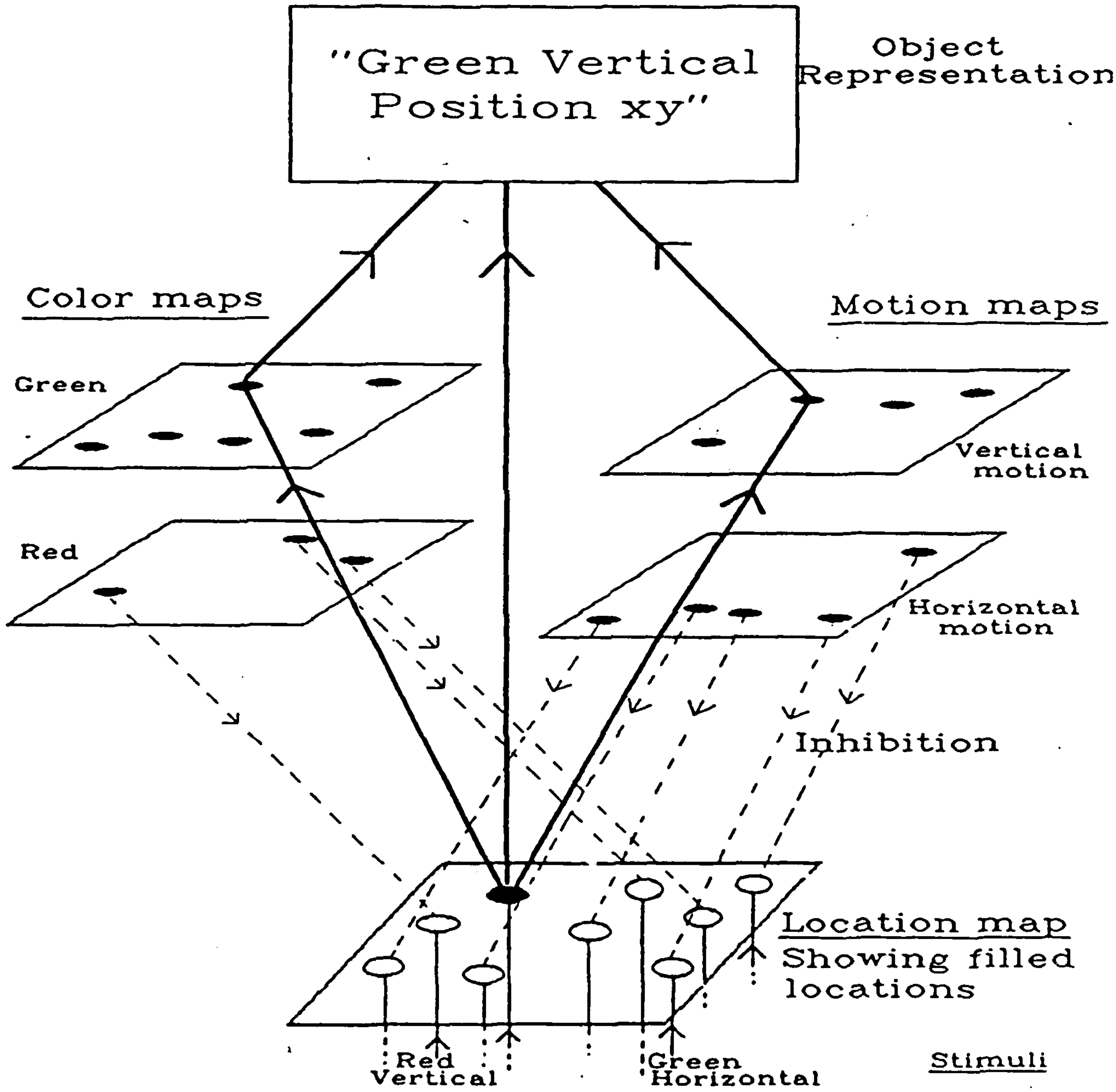


b)

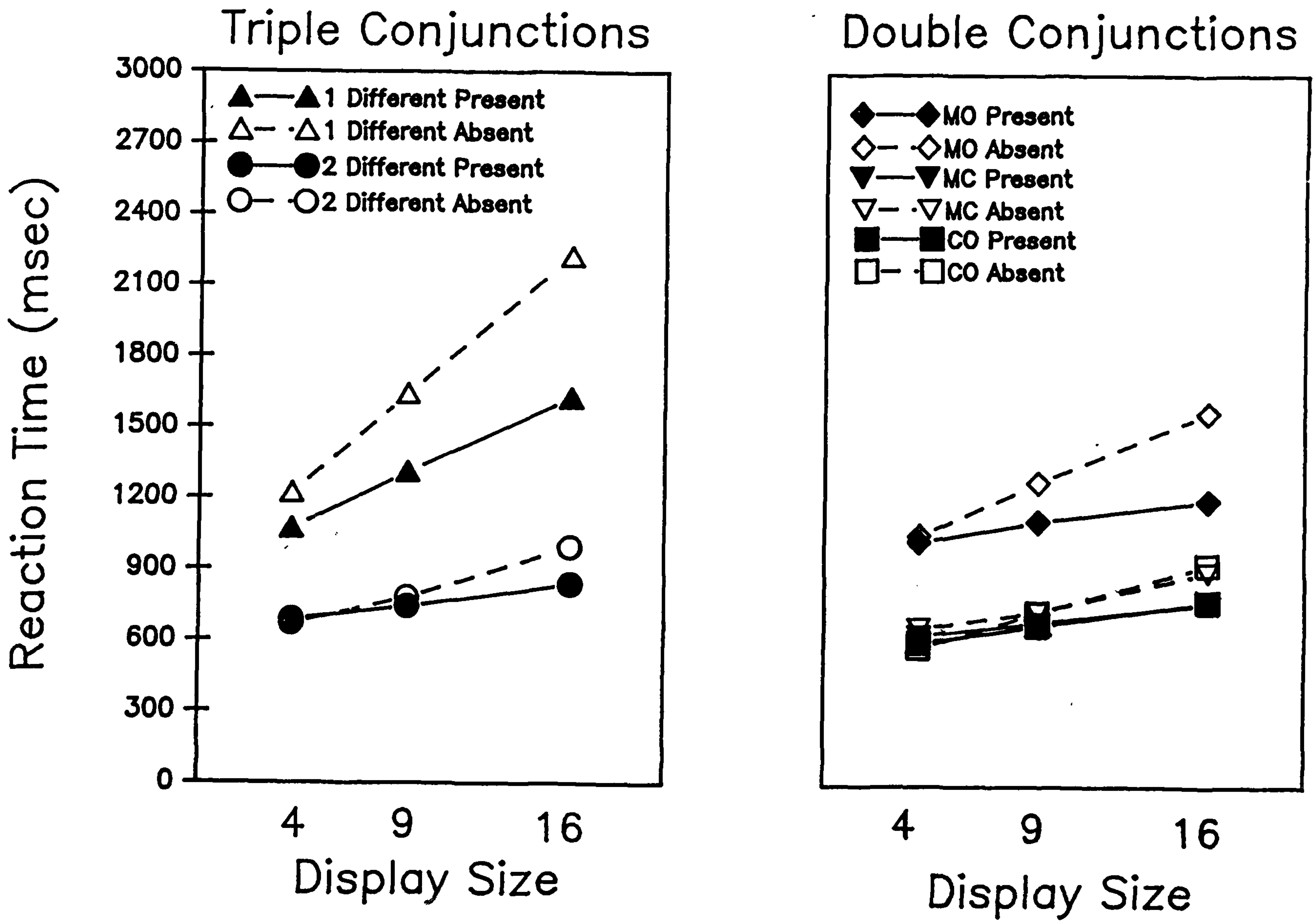




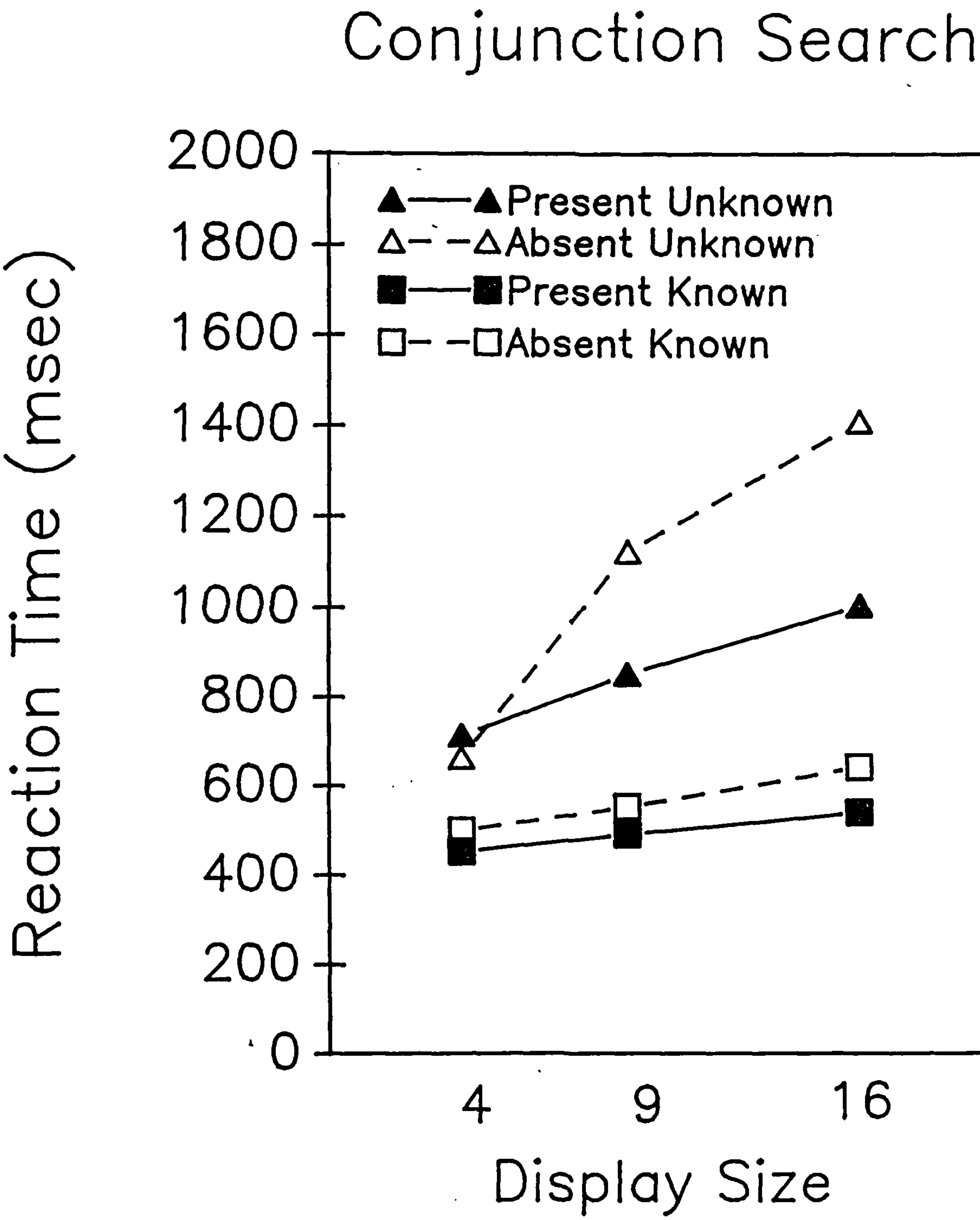
Reaction Time (msecs)
1700
1500
1300
1100
900
700
500
300
0
MC
MS
MO
CO
SO
CS
M
O
C
S
4
9
16
Display Size
Feature
Conjunction
Present
Absent



"Green Vertical Position xy"
Object Representation
Color maps
Motion maps
Green
Red
Vertical motion
Horizontal motion
Inhibition
Location map
Showing filled locations
Red Vertical
Green Horizontal
Stimuli

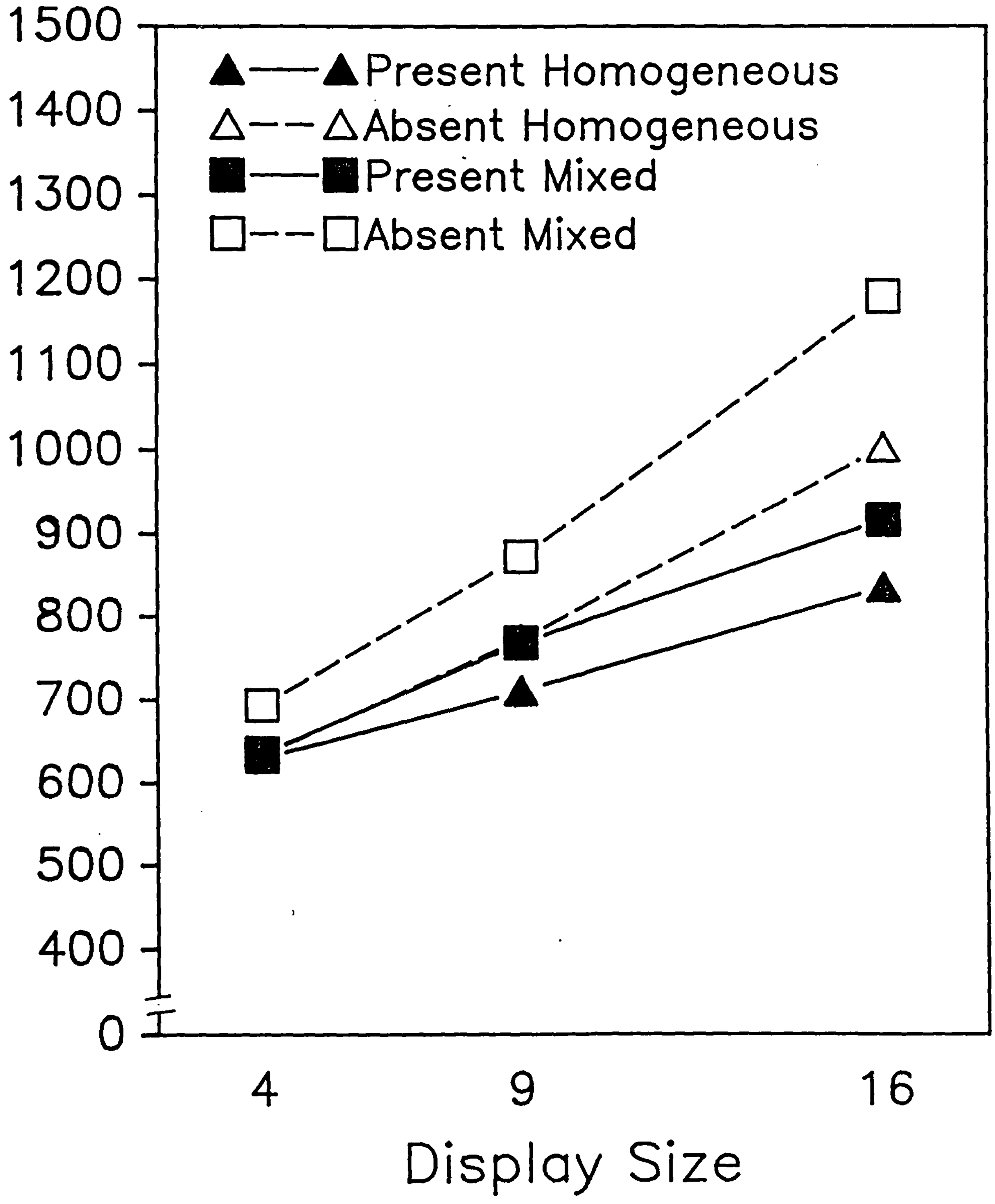


Triple Conjunctions
Double Conjunctions
Reaction Time (msec)
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
1 Different Present
1 Different Absent
2 Different Present
2 Different Absent
MO Present
MO Absent
MC Present
MC Absent
CO Present
CO Absent
4
9
16
Display Size
4
9
16
Display Size



Conjunction Search
Present Unknown
Absent Unknown
Present Known
Absent Known
Reaction Time (msec)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
4
9
16
Display Size

Conjunction Search with Two or Four Types of Distractors



Automatic Search: Changing Perceptions or Procedures?

Alfred Vieira and Anne Treisman
University of California, Berkeley.
Talk given at the Psychonomic Society meeting in Chicago,
November 11th, 1988.

Search through displays of complex patterns is typically serial. Even targets as simple as 2-line arrangements show linear increases in search time as extra elements are added to the display. T's among L's, pluses or arrows among their components, parallel among converging lines all show significant slopes to the search function. Yet Schneider and Shiffrin (Schneider and Shiffrin, 1977, Shiffrin and Schneider, 1977) showed that, after extensive practice in a consistent mapping paradigm, arbitrary sets of letters could be detected in parallel. So, for example, the letters P, S, G and V might all pop out of displays containing other randomly selected letters -- and even out of the newspaper the subject attempted to read when she went home! These sets of shapes seemed after learning to behave in search as if they were simple features -- red among black, or horizontal among vertical lines. What could have changed?

More generally, how do we account for automatization of skilled performance? Some theorists, such as John Anderson (Anderson, 1982), focus on the procedures used to perform a task; over practice, procedures become chunked together, 'compiled', speeding up responses and freeing performance from central control.

Schneider and Shiffrin (Schneider and Shiffrin, 1977, Shiffrin and Schneider, 1977), on the other hand, see automatization as the process of attaching both a learned <u>attention</u> response and the appropriate <u>motor</u> response to each of the practiced targets, making their detection independent of the limited resources used in controlled processing. They showed that practice had little effect in a varied mapping paradigm in which targets and distractors repeatedly reversed their roles. This makes it unlikely that automatization reflects only the learning of general procedures.

A third view proposed by David Laberge (LaBerge, 1973, 1976) emphasizes changes in the <u>perceptual representations</u> of relevant stimuli. He suggested that unfamiliar patterns initially depend on attention to link their component features. With repeated practice, their representations become more 'wholistic' and accessible, leading to a decreased need for attentional processing. Both these accounts predict that learning should transfer to new tasks using the familiar stimuli, but not to the use of new stimuli in the practiced task.

We will describe an experiment designed to explore the effects of automatization using more complex, initially unfamiliar patterns in a visual search task. The technique was to train subjects in the search task for 16 sessions (about 11,000 trials), and to compare their performance both before and after the training procedure in various <u>other</u> perceptual tasks using the same sets of stimuli or new ones. By looking at transfer of training from the automatized search task to other perceptual situations, we hoped to find out what had changed.

Figure 1 shows examples of the patterns we used. All were connected 6 line segments in a 3 x 3 array of dots. Subjects were asked to look for any of 4 targets among 1 to 4 distractors. We ran five subjects and counterbalanced which patterns each had as targets, as distractors and as unpracticed controls, to be used only in the transfer tasks.

The search task was initially very difficult. Search was slow and serial in the first session, averaging 134 ms/item (Figure 2).[1] But the search rates dropped steeply over the 16 sessions of practice, until they were down to only 16 ms/item. The decrease with practice followed the power function previously found in many skilled tasks.

Our main interest was to see whether the learning would transfer when the same target patterns were used in other perceptual tasks. We looked at mental rotation, detection of embedded parts, apparent movement, and subjective measures of goodness and liking for all 5 subjects. For two of the subjects, we added several further tasks and we also compared the control patterns that were partly familiar, because they appeared in all the transfer tasks, with completely new patterns seen only once each. This allows us to separate an initial perceptual familiarization effect from the overlearning induced by extended practice in search. Subjects were tested on these different transfer tasks both before and after the sessions of search practice. Let's look at them one at a time.

The first task was a mental rotation task (Figure 3a). We wondered whether practice in search would establish a unitized representation. Mentally rotating an over-learned pattern might be faster than rotating a new one. In fact, we found no difference. Three subjects were tested with successive presentation of the two patterns to be matched and five different orientations. The last two subjects were tested with a better procedure -- simultaneous presentation and nine different orientations. These subjects showed a more typical pattern of response times, increasing with the angle of rotation. However, there was no systematic effect of the search sessions (Figure 3b). The targets, the distractors and the control patterns gave very similar performance for both groups. The completely new patterns gave slower mean latencies. There seems to be an initial familiarization benefit, but no further transfer from automatization in search.

The second task also tested the idea that automatization produces a unitized Gestalt. This time we asked whether unitization makes the targets more difficult than control patterns to decompose mentally into their parts (Figure 4a). Subjects were asked to decide as quickly as possible whether a 3 line part was contained in the 6 line whole pattern when both were presented side by side. They were faster in the final session after the search training than in the initial session, but equally so on all the patterns (Figure 4b). Again, there was no hint of specific learning restricted to the targets.

The third task was an attempt to find transfer in a test of preattentive segregation and parallel processing. We asked whether a learned pattern would be seen in apparent motion when its position was shifted between two alternating displays, even though it was embedded among other randomly changing lines (Figure 5a). In other words, could the correspondence problem be solved and the embedded pattern matched across different positions in the alternating displays. Pantle (Pantle, 1973) showed that apparent motion can be seen when the correspondence between groups of embedded elements is based on color; Treisman and Sato (Treisman and Sato, in prep) have shown the same for color, orientation and size, and Ramachandran (Cavanaugh, et. al., 1989) for shape from shading. Here we ask whether automatization in search establishes a preattentive matching process for a more complex global pattern. The subjects were asked to discriminate between horizontal, vertical and diagonal motion of the embedded pattern. We found a substantial generalized improvement, for new patterns as well as old, and this time there was also a slightly greater benefit for both the familiar targets and the distractors relative to control patterns and completely new patterns (Figure 5b).

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[1] mean slope figured as (2pos + neg) / 2

It is interesting that perceptual experience can affect the correspondence process which mediates apparent motion, since this is generally assumed to be an automatic, preattentive process. Even here, however, the difference was only 29%[2]; it reached significance for only one subject ($X^2_{(1)} = 8.54$), and the search distractors benefited almost as much as the targets, contrary to the predictions based on a learned attention response.

Having found so little transfer in the previous three tests, we thought it important to probe further the generality of the conclusions. With our last two subjects, we tried some additional tests that we hoped would be more specifically perceptual -- a threshold identification task with masked displays and an iconic memory task.

The patterns in the threshold task were presented in a brief interval between two masks and subjects made a same-different matching decision between the masked pattern and an unmasked pattern. Both subjects also made a rating of subjective clarity. In one condition, the masked pattern preceded the unmasked pattern and in the other condition it followed it. When the masked pattern came first, there was again a slight advantage for the targets over the control patterns (10%). This effect was significant for only one of the two subjects ($X^2_{(1)} = 6.51$). When the masked target was second, there was no difference. Nor was there any difference in the ratings of perceived clarity; separate ANOVAs comparing target stimuli to controls and controls to new stimuli showed no effect for either subject. Thus, automatization in search makes it slightly easier to find a pattern embedded in a rapid sequence between two masks, but the advantage is wiped out if the unmasked pattern has been given immediately before the masked one.

The iconic memory task provided only negative results (Figure 6). The displays of 3 patterns (all targets or all control patterns) were briefly flashed, followed by a probe pattern in the empty location either 100 or 500 msec later. Subjects judged whether the probe had appeared in the initial display. Although this task should benefit from parallel coding, there was again no benefit at all for the learned target patterns relative to controls.

One final task, that all 5 subjects performed, was the only one to show effects of the search automatization. Subjects were asked to rate the patterns both for 'goodness' (in the Gestalt sense) and for likability. They judged their own targets 'better' as patterns and definitely more likable than the controls (Figure 7). The 16 sessions of practice were not to no avail! -- we did after all replicate the mere exposure effect. Detecting presence or absence can make the heart grow fonder.

More seriously, we think we also learned some significant facts about the process of automatization. Whatever perceptual learning takes place seems to be highly specific to the learned task: it transfers only to the apparent motion task and to the masked threshold task (and that to a very limited degree). Notice that both tasks included a component of search: subjects had to disembed the coherently moving pattern from the background lines that changed at random, and to disembed the masked pattern from the temporally surrounding masks.

Shiffrin and Schneider's (Schneider and Shiffrin, 1977, Shiffrin and Schneider, 1977) account in terms of a learned attention response might help to explain the absence of transfer to most of the other tasks described so far, since most presented single rather than multiple stimuli. There was generally no need to divide attention. However, an earlier experiment we ran with letters suggested that this may not be the critical factor. We trained four subjects in search for 3 target letters and then tested transfer to a texture segregation task, involving arrays of 49 letters (7 x 7 matrix). The question was: would a central 3 x 5 rectangle containing

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[2] difference expressed as a percentage of performance on control stimuli

only the target letters form a salient figure against a background of other letters in the remaining cells (Figure 8). The task was to decide whether the target rectangle was vertically or horizontally oriented. Again, we found no difference whatever in the latency for the learned targets compared to control letters. Note that the iconic memory task, which was also a divided attention task, also showed no advantage for the learned targets.

The results surprised us -- perhaps reflecting our initial naiveté -- so we ran some further tests within the search paradigm to see how specific the learning was in the context of the original training procedure. We tested two of the same subjects with 4 new targets among the same distractors. There was some transfer: search rates averaged 105 ms/item. This can be compared to a session in which they had both new targets and new distractors, in which the search rates averaged 219 ms/item; this comparison was significant for both subjects. Transfer in this session was quite incomplete, though, if you compare it to their last session of practice, where search rates averaged 17 ms/item; this comparison was also significant for both subjects. The results contrast sharply with those of Dumais (Shiffrin and Dumais, 1981) who found almost perfect transfer using alphanumeric stimuli. Keeping the targets constant but changing the distractors, on the other hand, gave very substantial transfer in our task as well as in Dumais': search rates decreased by only 6 ms/item (Figure 9). This difference was significant for one subject ($F_{(1,792)} = 4.77$, $p > .029$). Learning with our initially unfamiliar patterns seems, then, to be more specific to the practiced targets, and less to the distractors.

If our subjects had learned an automatic attention response, their performance should be severely compromised if they were exposed to a condition in which they searched for new targets, with their former targets appearing among the items in the distractor set. This condition has been used as a diagnostic for search automatism by Shiffrin and Schneider (Schneider and Shiffrin, 1977, Shiffrin and Schneider, 1977). We performed this control and found that our subjects' mean search slopes increased from 26 to 79 ms/item. Their accuracy also decreased by 8%. Although this change in slope is substantial and was significant for both subjects, it is not as severe as the decrement that other investigators have shown. The accompanying change in accuracy suggests that the difference was due to a speed-accuracy tradeoff; our subjects accepted higher error-rates to achieve a smaller drop in speed than those in other experiments.

We also performed another experiment to see if targets are learned individually or as a category. We ran our normal search procedure, but replaced one of the four targets for each subject with a completely new target. Search rates on positive trials when the unchanged targets were presented increased from 13 to 23 ms/item; a significant change for both subjects. This indicates that at least to some degree, subjects were learning a class of target figures as well as learning the figures individually.

In our final two experiments, we changed irrelevant spatial and visual details of the displays. In one condition, we changed the spatial arrangement in which the 1 to 4 patterns could appear from a diamond-shaped array to a horizontal line. Everything else was unchanged: yet the search slopes trebled, from 16 to 46 ms/item, setting the search skill back to the point it had reached around session 5 of the original practice procedure (Figure 10). This difference was reliable for both subjects.

Finally, we tested the trained stimuli in the original lay-out but with reversed contrast: instead of green lines on a black background, we used black lines on a green background. Here, the search slopes increased from 26 to 35 msec/item; the difference was reliable for only one of the two subjects. Even small and irrelevant changes in the appearance of the displays seem to decrease the automaticity of search.

Since it is possible that the reversed contrast and changed spatial arrangement tasks could simply involve more difficult perceptual discriminations, we ran six subjects who experienced these and the normal variation of the search task in a blocked, counterbalanced design with no learning. The differences in the details of the displays had no effect on the search performance of these subjects.

What can we conclude about learning in the course of search automatization? Tables 1 and 2 summarize the results we've described. The results seem to rule out two simple and opposite general hypotheses. Extended practice in a particular perceptual-motor skill neither changes the visual coding of the learned targets in a way that generalizes to other tasks, nor changes the procedures within the learned task in a way that generalizes to new stimuli. Thus, we found little support for the idea that automatization in search generates new unitized representations which behave in other contexts like functional feature detectors. There seem to be limits to the plasticity of the visual system. On the other hand, extended practice does not simply automatize the procedures of searching the display and selecting the appropriate response. Even irrelevant changes in the visual details and spatial arrangements of the old stimuli disrupt the speed and efficiency to some degree. The general message is one of striking specificity in the learning process.

The results are consistent with recent accounts of expertise as the accumulation of a large data-base of highly specific memories which guide performance on new examples. Herbert Simon (Simon and Chase, 1973) proposed a memory-based account of expertise in chess; the Dreyfuses (Dreyfus, H.L, and Dreyfus, S.E., 1986) extended it to other skills, and Gordon Logan (Logan, 1988) has very recently expressed and tested it as an exemplar model of automatization. On this view, the display presented on any trial selectively evokes traces of the most similar earlier trials, together with the response that was made. These traces somehow select and speed the current response. The memories are specific to the particular targets in the particular sets and spatial arrangements that were practiced. They facilitate repetitions to the degree that these resemble the earlier trials.

For future research, the question will be whether we can somehow push the system to abstract and to generalize. Perhaps the accumulation of specific memories is the only form of skilled learning, but perhaps the specificity we found resulted from the very restricted context of learning. It seems possible that varied practice would encourage the formation of declarative, perceptual representations that become independent of the particular procedures that use them. Alfred Vieira is now using the same stimuli and tasks to test whether subjects who are trained in three different perceptual tasks instead of one will show better transfer to other new tasks. If, however, automatization depends on the retrieval of specific memory exemplars, it should still be restricted to the particular subset of tasks that the subject has learned.

References

Anderson, J.R., 1982, "Acquisition of Cognitive Skill", Psychological Review, 89(4), 369-406.

Cavanaugh, P., Ramachandran, V.S., Treisman, A., and Van der Heydt, R., 1989, "The perception of form: striate cortex and beyond", in Spillman, L. and Werner, J. (Eds.), *Neurophysiological Foundations of Visual Perception*, Academic Press, in press.

Dreyfus, H.L. and Dreyfus, S.E, 1986, *Mind over Machine*, Free Press, New York.

LaBerge, D., 1973, "Attention and the measurement of perceptual learning", Memory and Cognition, 1(3), 268-276.

LaBerge, D., 1973, "Perceptual Learning and Attention", in Estes, W.K. (Ed.), *Learning and Cognitive Processes*, 4 , Lawrence Erlbaum Associates, Hillsdale, N.J.

Logan, G., 1988, "Toward an instance theory of automatization", Psychological Review, 95(4), 492-527.

Pantle, A.J., 1973, "Stroboscopic movement based upon global information in successively presented visual patterns", Journal of the Optical Society of America, 63, 1280.

Schneider, W. and Shiffrin, R.M., 1977, "Controlled and Automatic Human Information Processing: I. Detection, Search, and Attention", Psychological Review, 84(1), 1-66.

Shiffrin, R.M. and Schneider, W., 1977, "Controlled and Automatic Human Information Processing: II. Perceptual Learning, Automatic Attending, and a General Theory", Psychological Review, 84(2), 127-190.

Shiffrin, R.M. and Dumais, S.T., 1981, "The Development of Automatism", in Anderson, J.R. (Ed.), *Cognitive Skills and their Acquisition*, Erlbaum Associates, Hillsdale, N.J.

Simon, H. A. and Chase, W. G., 1973, "Skill in chess", American Scientist, 61(4), 394-403.

Table 1

Performance after Search Practice: Difference Between Stimuli as a Percentage of Performance on Control Stimuli

New Tasks			Target - Control		Control - New	
Mental Rotation	Slope	(N = 2)	-2		18	
	Mean RT		-5		-26	¥
	Accuracy		8	£	6	
Parts in Wholes	RT	(N = 5)	-3		--	
	Accuracy		0		--	
Apparent Motion	Accuracy	(N = 2)	26	$	0	
Iconic Memory	Accuracy	(N = 2)	-1		6	
Threshold:						
Masked first	Accuracy	(N = 2)	10	£	3	
Masked Second	Accuracy	(N = 2)	1		5	
Clarity	Rating	(N = 2)	0		11	
Likability	Rating	(N = 5)	29		--	
Goodness	Rating	(N = 5)	22		--	
Texture Segregation (for letters)	RT	(N = 4)	0		--	

¥ significant for all subjects
$ significant for one subject, $p < .01$
£ significant for one subject, $p < .05$

Table 2

New Variations of Search Task

Variation	Change in search rate[3]	Change in mean RT
New Targets	89	167 ¥
New Distractors	6	9 £
Old Targets when combined with one new target[4]	10	70 ¥
Old Targets part of distractor set	53	155 ¥
Reversed Contrast	9	17 $
New Spatial Configuration	30	38 ¥

¥ significant for both subjects
$ significant for one subject, $p < .01$
£ significant for one subject, $p < .05$

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[3] rate is (2pos + neg) / 2 except where noted
[4] rate reported for positive trials only

Fig.1

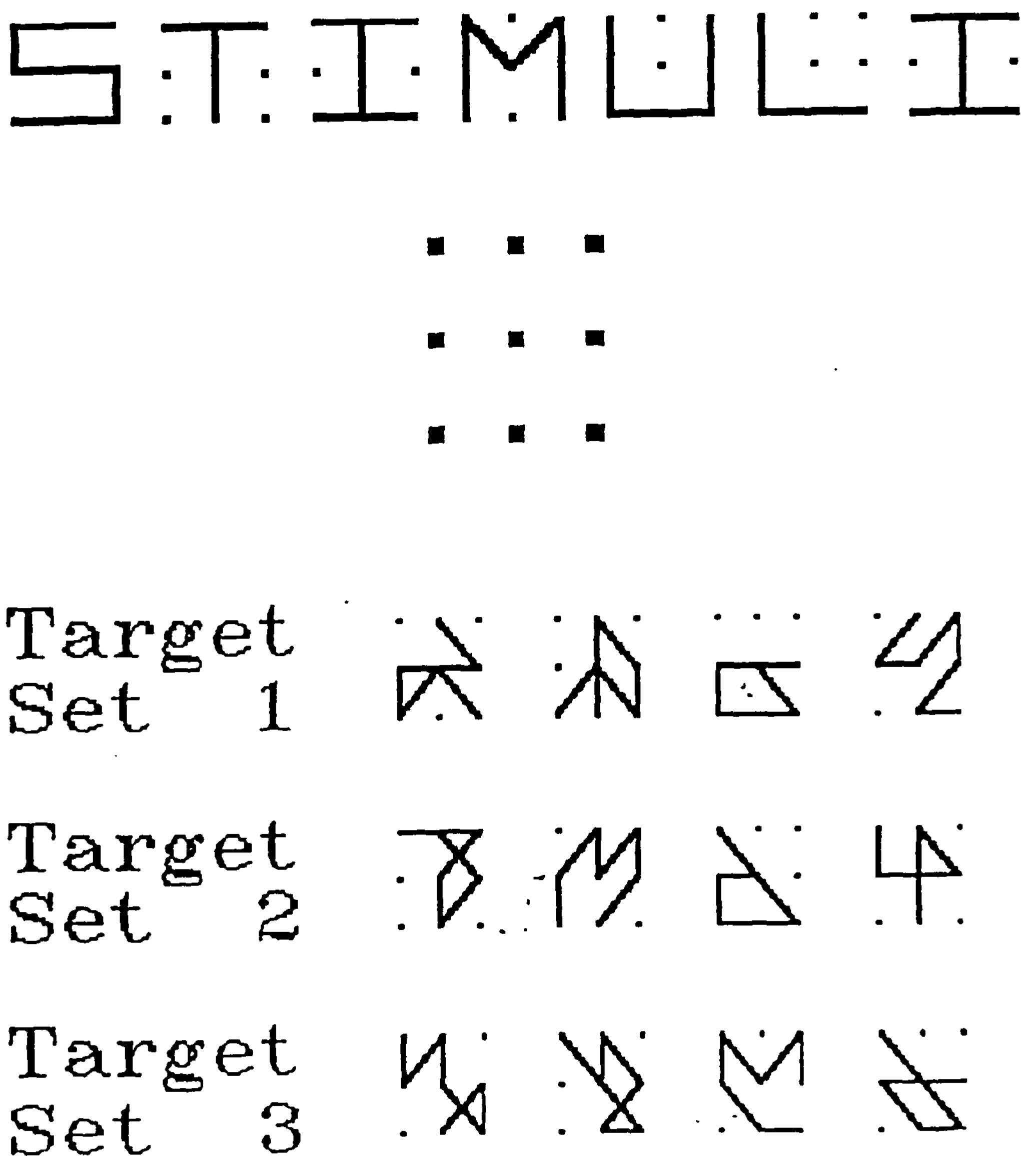
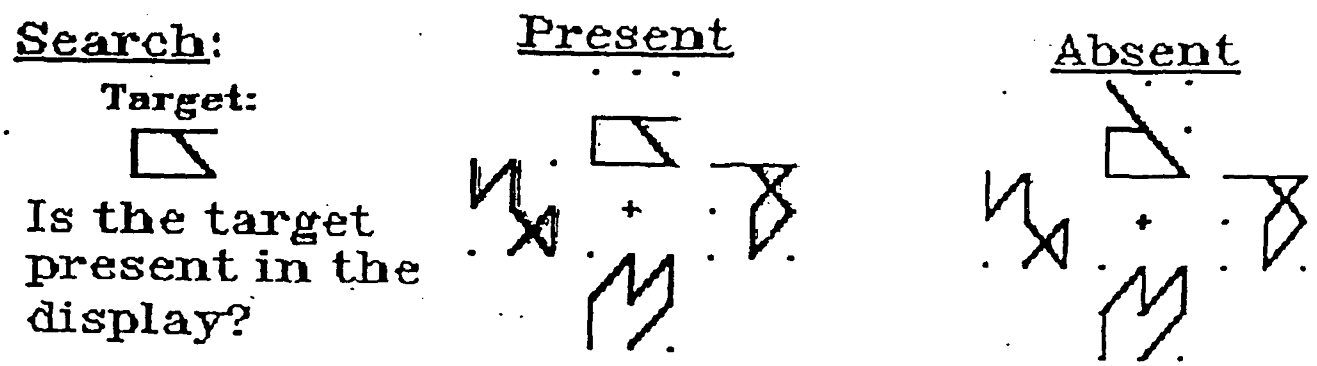
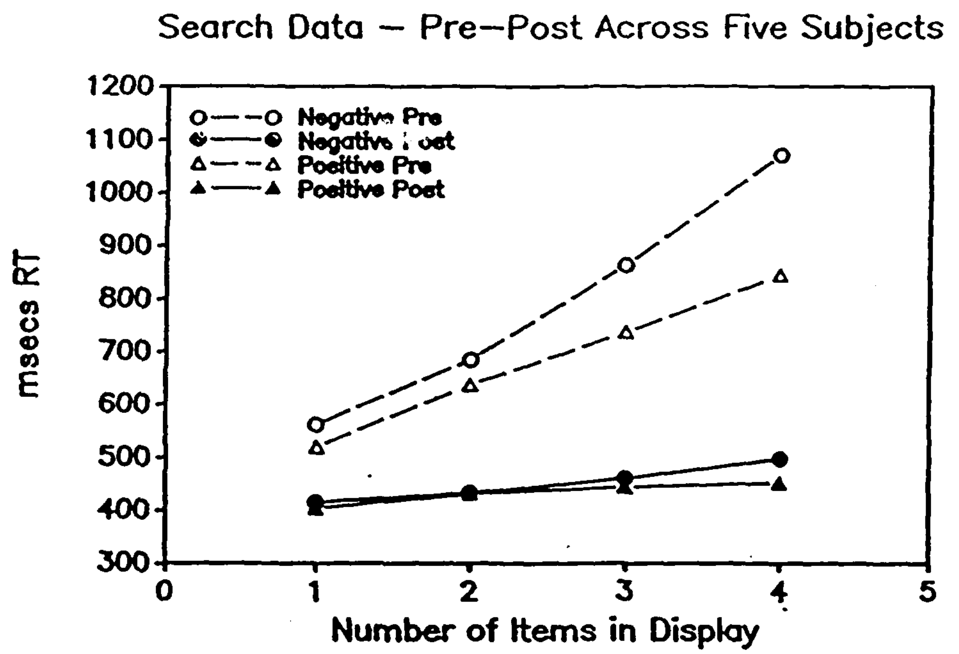


Fig. 2


Search:
Target:
Is the target present in the display?
Present
Absent


Search Data – Pre–Post Across Five Subjects
Negative Pre
Negative Post
Positive Pre
Positive Post
msecs RT
1200
1100
1000
900
800
700
600
500
400
300
0
1
2
3
4
5
Number of Items in Display

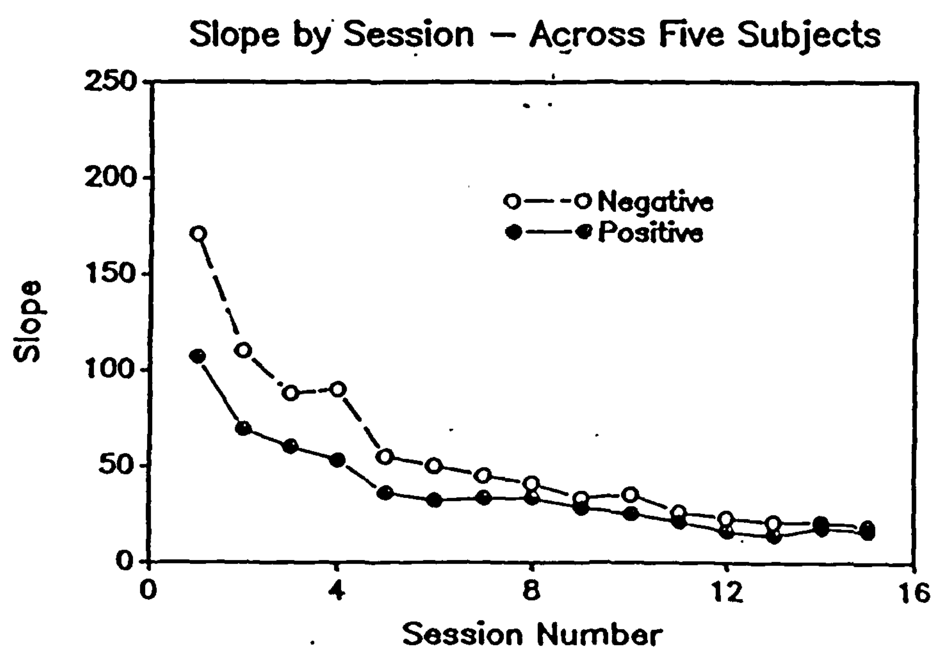

Slope by Session – Across Five Subjects
Negative
Positive
Slope
250
200
150
100
50
0
0
4
8
12
16
Session Number

Fig. 3

Mental Rotation:

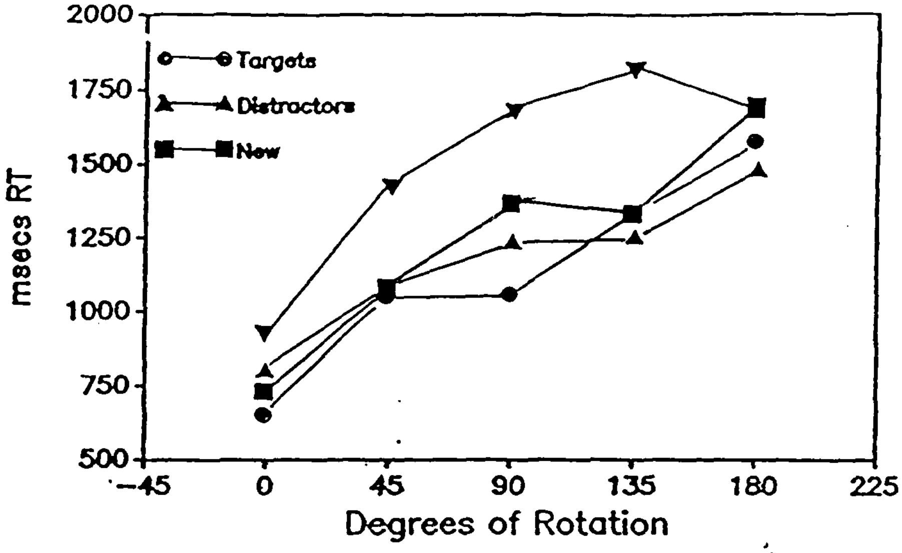
Standard:

Is the rotated figure a normal or reflected version of the standard?

Normal

Reflected

Simultaneous Presentation Rotation — Two Subjects



Successive Presentation Rotation — Three Subjects

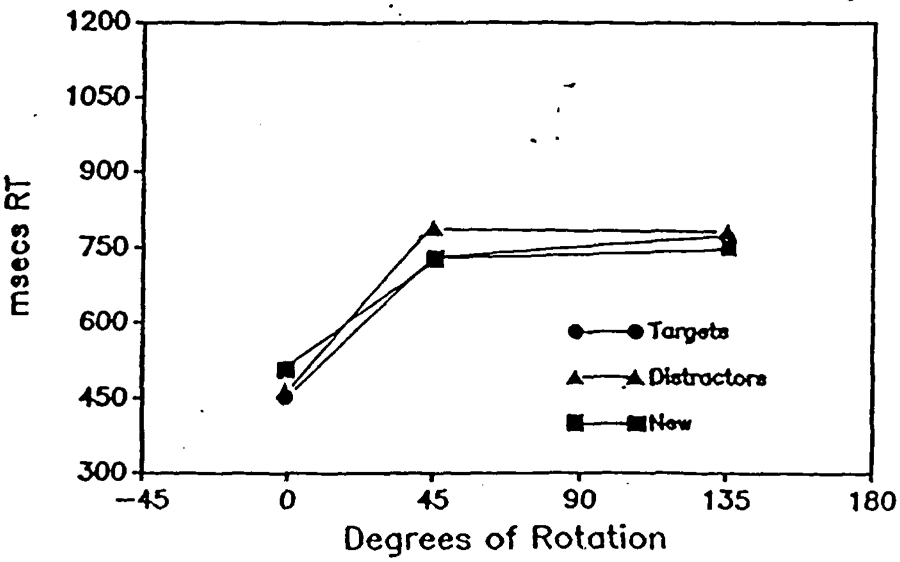
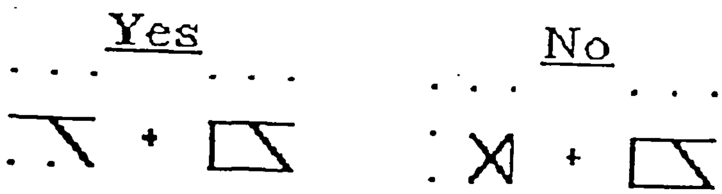


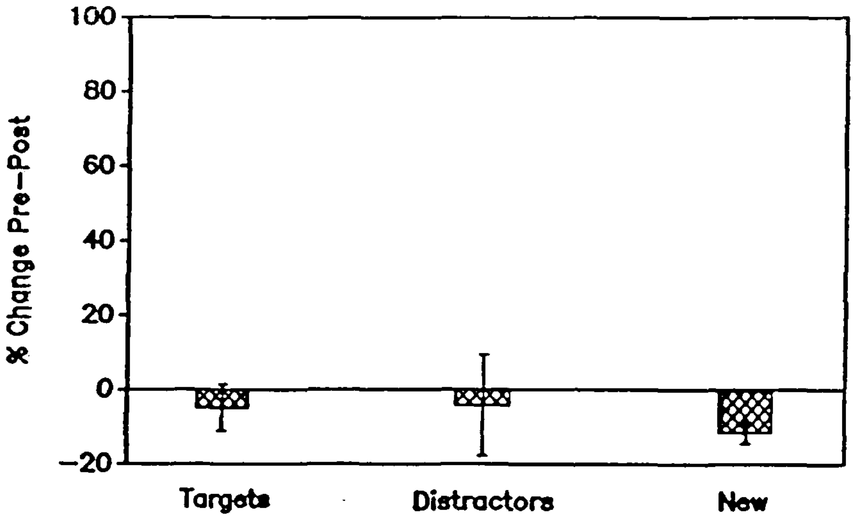
Fig. 4

Parts in Wholes:

Is the part present in the whole?



Parts in Wholes — Percent Change in Accuracy



Parts in Wholes — Percent Improvement in RT

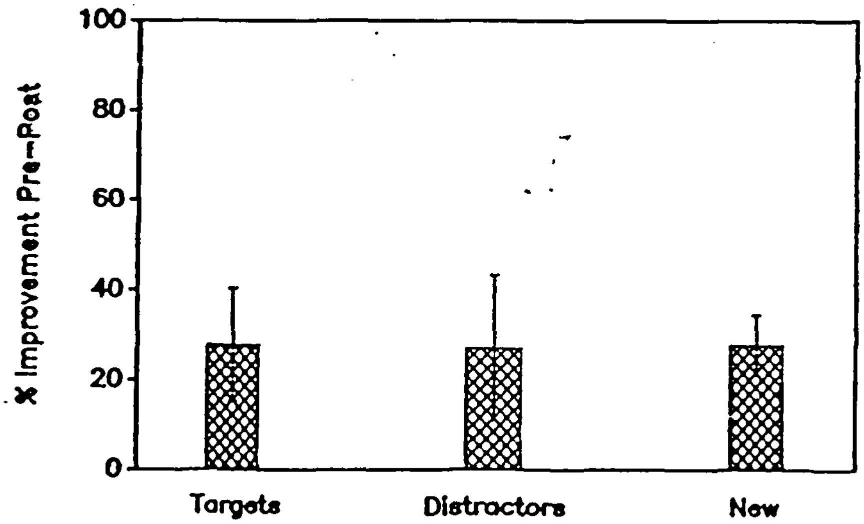


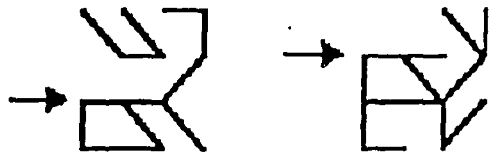
Fig. 5

<u>Coherent Motion</u>:

Target:

Is the target moving vertically, horizontally, or diagonally against the background?

<u>Vertical Movement</u>



These displays alternate

Coherent Motion — Improvement in Percent Correct

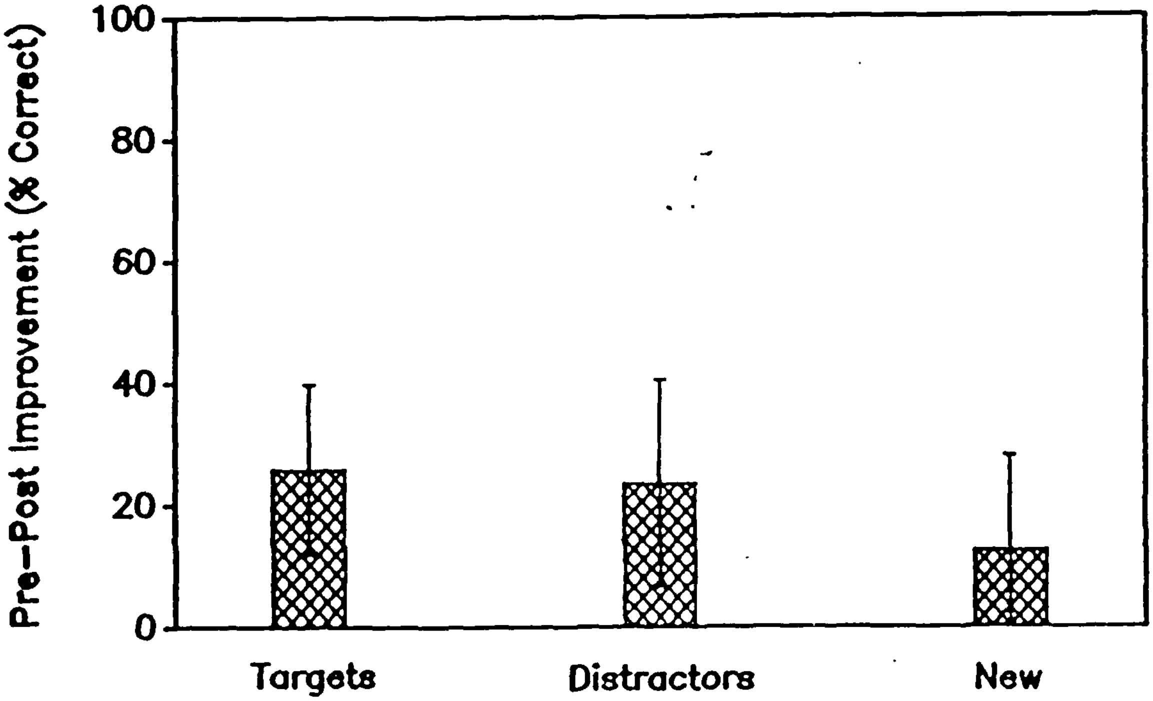


Fig. 6

Iconic Memory:

Was the probe present in the display?

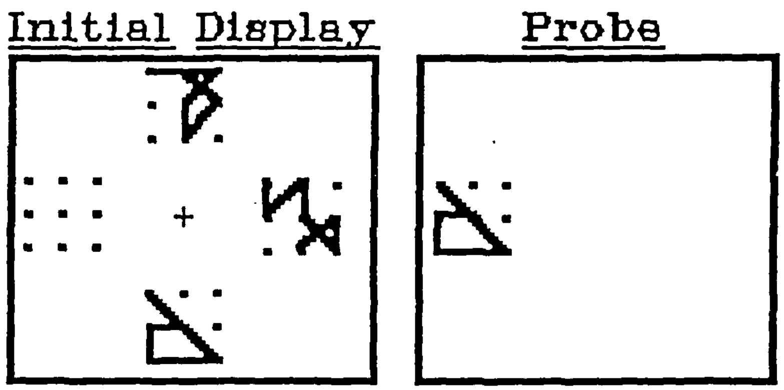


Fig. 7

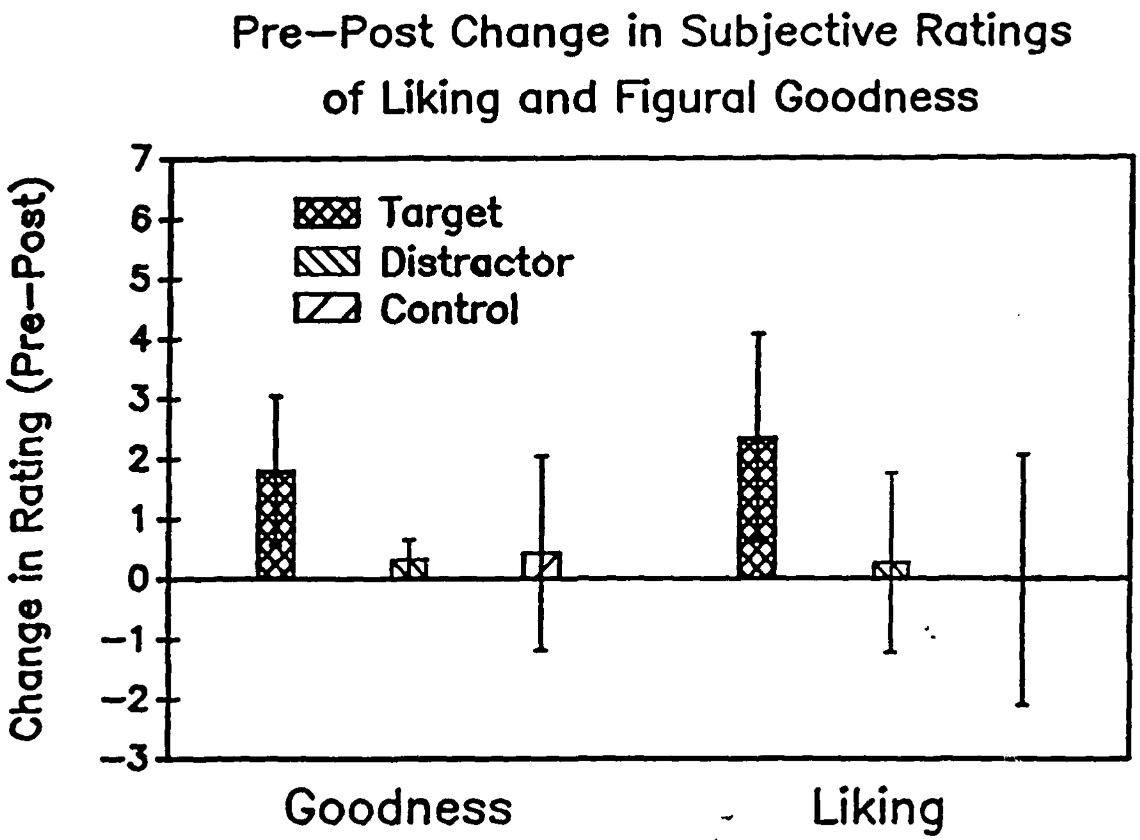

Pre–Post Change in Subjective Ratings
of Liking and Figural Goodness
Change in Rating (Pre–Post)
7
6
5
4
3
2
1
0
−1
−2
−3
Target
Distractor
Control
Goodness
Liking

Fig. 8

Texture Segregation:

Is the area defined by the targets (TVQ) vertical or horizontal?

Vertical

A	G	J	H	K	S	N
U	T	Q	T	B	C	A
D	V	T	Q	C	G	J
C	V	V	T	H	M	N
M	Q	Q	V	S	U	B
D	V	T	T	B	K	S
K	U	A	C	D	H	J

Horizontal

A	G	J	H	K	S	N
U	T	Q	V	T	V	A
D	Q	Q	V	T	T	J
M	V	T	V	Q	T	B
K	U	A	C	D	H	J
C	G	J	K	N	S	B
D	M	N	K	H	J	A

Fig. 9

Search Slopes: Standard Task and Three Variations

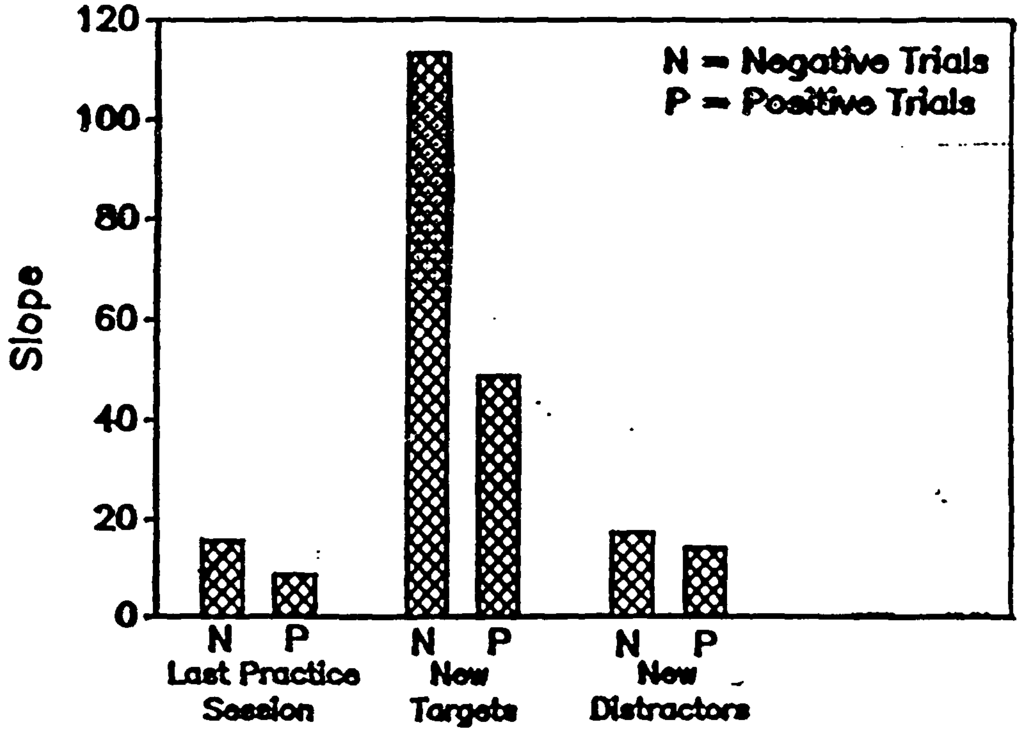
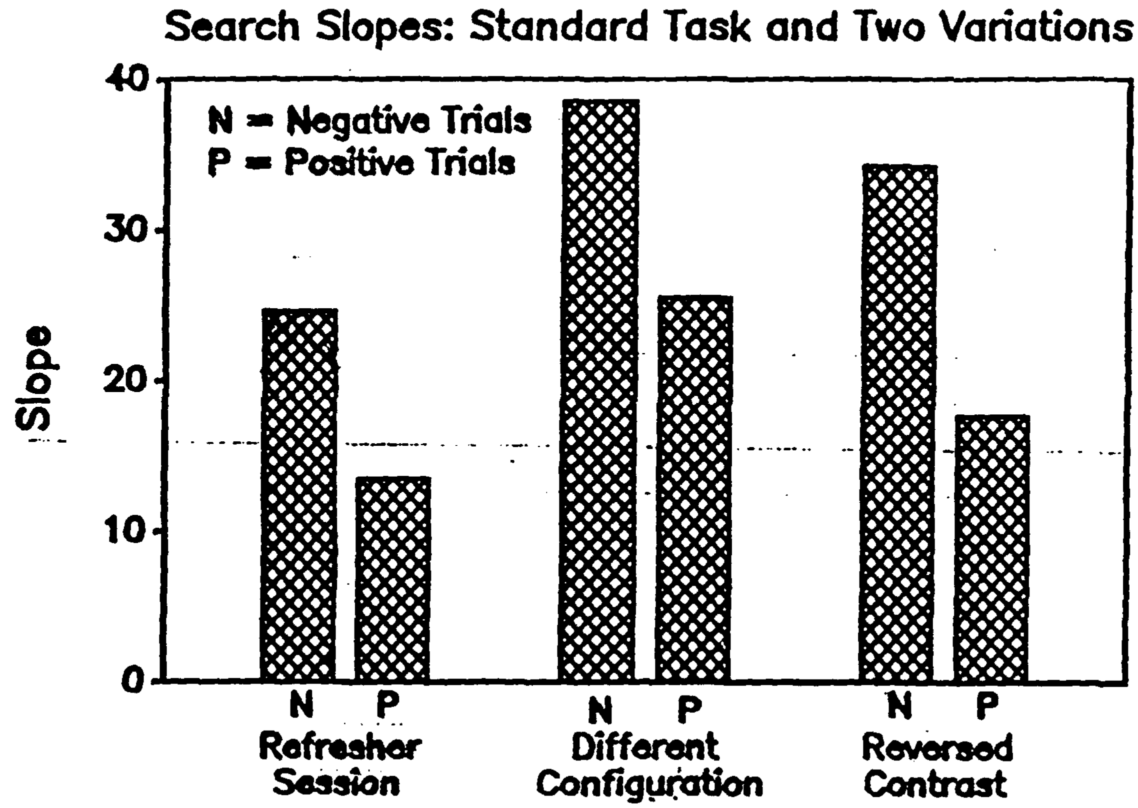


Fig. 10


Search Slopes: Standard Task and Two Variations
N = Negative Trials
P = Positive Trials
Slope
0
10
20
30
40
N
P
Refresher Session
N
P
Different Configuration
N
P
Reversed Contrast

Effect of Stimulus Domain on Visual Search For Orientation and Size Features

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Running head: Visual search

Key words: Visual search, multiple representations, vision

ABSTRACT

Using a visual search task, the encoding of orientation and size was studied in five different stimulus domains: luminance, color, texture, relative motion and binocular disparity. The results indicate that early encoding of orientation and size may occur in each of the five domains studied, with the possible exception of the binocular disparity domain.

INTRODUCTION

Elementary Features

Vision has two goals: first, to determine the spatial layout of surfaces in the scene and second, to identify objects. In achieving these goals, it is likely that the visual system first encodes low-level features of the image. The nature of these low-level features, or coding primitives, of vision, has been central to a wide range of research from Gibson's (1950) study of letter features to Julesz's (1981) textons.

Treisman (Treisman & Gelade, 1980; Treisman, 1985; Treisman & Souther, 1985) has proposed a number of behavioral criteria that can be used to identify elementary features. For example, since elementary features are critical to the initial segregation of object surfaces, the visual system should be able to process these features simultaneously at all positions across the visual field. In particular, a stimulus that differs from a field of distractors by a single, elementary feature should be distinguished effortlessly from the background. Several studies have shown that this property (labeled parallel processing, or "pop-out") does occur with targets defined by certain visual features, including among others, a distinctive orientation, size, direction of motion, or color, or by the presence of terminators or closure (Neisser, 1963; Egeth, Jonides & Wall, 1972; Treisman & Gelade, 1980; Bergen & Julesz, 1983; Treisman, 1985; Arguin & Cavanagh, 1988; Treisman & Gormican, 1988). The features identified by the parallel processing criterion are considered to belong to the set of primitives used by the visual system.

Physiological studies have shown that many units in the monkey visual cortex are tuned to respond selectively to features that are in many cases similar to those identified by behavioral criteria in the visual search task. Hubel and Wiesel (1968) described simple and complex cells that had well defined preferences for particular orientations and sizes. Other cells show directional selectivity (Movshon, Thompson & Tolhurst, 1978), color selectivity (Zeki, 1973; 1978), and disparity selectivity (Bishop, 1973; Poggio & Fisher, 1977). It has also been proposed that end-stopped cells (Hubel & Wiesel, 1965) might underlie the processing of line terminators (von der Heydt, Peterhaus & Baumgartner, 1984) and curvature (Dobbins, Zucker & Cynader, 1987). Such units could be the basis of the performance in behavioral tasks.

Separate Visual Pathways

Physiological results with monkeys also suggest a hierarchy of analysis that starts with color and luminance at the retinal ganglia (DeValois & DeValois, 1975; Gouras & Eggers, 1982). At the level of the striate cortex, units emerge that are selective to the orientation, binocular disparity and relative motion of local contours defined by color or luminance. The processing of different aspects of visual information separates first into local regions of the striate cortex, for example, blob and interblob regions specialized for color and luminance, respectively (Livingstone & Hubel, 1987), and then into functionally distinct extrastriate cortices. Zeki (1973, 1978), Allman and Kaas (1976), van Essen (1985), van Essen and Maunsell (1983) and others have described this separation of function for different extrastriate regions; in particular, area V4 appears to be specialized for the analysis of color, and area MT for motion.

The reports of brain-damaged humans who show visual deficits specific to motion, color or luminance also indicate that different visual attributes may be represented in separate regions of the visual cortex. Damage to one region may then affect only the analysis of one visual attribute. For example, Zihl, Von Cramon and Mai (1983) have reported a patient who is motion-blind. For this patient, tea being poured from a pot appears to be frozen in space. Botez (1975) reports the converse case of patients incapable of identifying objects unless they move. Damasio, Yamada, Damasio, Corbett and McKee (1980) describe case histories of cortically colorblind patients who only perceive in black and white. Rovamo, Hyvärinen and Hari (1982) have described a luminance-blind patient. This patient sees no shapes in a black and white television image but sees color television perfectly well. Reports of the selective loss of binocular depth vision (Carmon & Bechtoldt, 1969; Benton & Hécaen, 1970) have also been published.

Both these physiological and clinical results suggest the existence of physically separate cortical areas specialized for the analysis of independent visual attributes. Each of these areas performs some specialized analysis of the represented attribute but each should also be capable of representing 2-D shape. That is, the visual cortices, up to the level of the inferotemporal cortex, retain a fair degree of retinotopy (see Maunsell & Newsome, 1987, for a review) so that the spatial properties of the retinal image are preserved. Each area could therefore constitute a separate map of the regions and discontinuities that are defined in the image by the attribute analyzed in that cortical area. In functional terms, these cortical areas may be thought of as way stations of an intertwined set of processing pathways, each analysing and representing a different aspect of the

visual world. The separate representations of shapes may provide complementary sources of information for object recognition, allowing the reduction or elimination of ambiguities that are present in each separate domain. Each may also provide more specialized information for other visually controlled tasks such as reaching and grasping, judging the affordances of surfaces, or predicting motion and change.

To study the separate contribution of each pathway, we can define images by variations in a single attribute, for example, color, relative motion, luminance, texture or binocular disparity. With these images, we can test the ability to encode shapes and to recover scene properties from the 2-D image defined by each of these attributes. Julesz (1971), for example, showed that we can perceive shapes defined only by binocular disparity in random-dot stereograms. Recent studies by Cavanagh (1987) have made similar demonstrations for images defined by color, relative motion and texture.

Elementary Features in Separate Visual Pathways

If we are capable of representing 2-D shape with these attributes, it becomes interesting to explore the elementary features used to code shape in each of the separate pathways. Does the analysis for each attribute rely on the same set of coding primitives, such as, size, orientation, terminators, and curvature, that were identified earlier for luminance-defined stimuli? Or is the set of features restricted, given the reduced resolution inherent in representations other than luminance?

There is already some evidence, both psychophysical and physiological, concerning the shape-coding primitives used by the separate extrastriate pathways. Physiological experiments have shown orientation and size tuning for color selective cells in area V1 of the monkey (Michael, 1978; Thorell, DeValois & Albrecht, 1984) and V4 (Zeki, 1978). More recently however, Lennie, Sclar and Krauskopf (1985) failed to find orientation tuning in V1 cells that were primarily selective for color. So far, there have been no reports of selective tuning for orientation or size among cells responding to regions defined by relative motion (Hammond & McKay, 1977; Hammond & Smith, 1982), binocular disparity (Poggio, Motter, Squatrito & Trotter, 1985) or texture (Nothdurft & Li, 1985). Psychophysical results, however, have shown tilt aftereffects for stimuli defined only by color differences (Flanagan, Cavanagh & Favreau, 1987) and by differences in texture, movement, and binocular disparity (Tyler, 1975;

Cavanagh, Flanagan & Arguin, 1987). Such results suggest that orientation processing does occur within these stimulus domains. Similarly, size aftereffects have been observed for stimuli defined by color (Favreau & Cavanagh, 1981) and binocular disparity (Tyler, 1975).

In the present experiment, we used a visual search paradigm to evaluate the elementary features available in five different stimulus domains. The targets differed from the distractors in one of two feature dimensions: either size or orientation. The two values on each dimension were selected to be highly discriminable so that processing would not be serial simply because the features were too similar (Treisman & Souther, 1985). The stimuli (both targets and distractors) were defined by discontinuities in each of five domains: luminance, color, texture, movement or binocular disparity. The number of stimuli presented on any trial varied from one to six and, on half of the trials, one of the stimuli was the target. We analyzed the search rate for these displays, that is the increase in the time necessary to detect a target as a function of each additional distractor. It was assumed that whenever the slope of the function relating search time to the number of items was not significantly greater than zero on *positive* trials, the distinction between the target and distractors was processed in parallel within a given stimulus domain, and was thus available as a privileged or elementary feature in early processing (Treisman, Sykes & Gelade, 1977; Treisman & Gelade, 1980; Treisman & Souther, 1985). We also investigated, for all five stimulus domains and for both feature dimensions, whether there were any search asymmetries (Treisman & Souther, 1985), the search rate being dependent upon which value within the relevant dimension (e.g. vertical or oblique orientation) defined the target.

METHOD

Subjects: Eight experienced psychophysical observers (four males and four females; average age, 28 years) took part in the experiment. All were right-handed and had normal or corrected sight, normal color vision and were able to see depth in random-dot stereograms.

Stimuli: The experiment was controlled by a Grinnell graphics system. The stimuli were displayed on a Conrac 5411 color video monitor.

The two stimuli used for orientation discrimination were solid rectangles of 1.5° by .5° of visual angle, oriented either vertically or at 45° with their top to the right. The two stimuli used for size discriminations were filled disks subtending either 1° or 1.5° of visual angle.

The stimulus display subtended 8° of visual angle at a viewing distance of 1.93 m. Its

average luminance was 26 cd/m^2. Except where stated otherwise, the target and distractors were filled with a random dot texture of 32 dots per degree, density of 50%, and contrast of 75%. The one to six stimuli that made up a given display were distributed randomly within a set of 18 possible locations situated at the intersections of three concentric circles (radius of 1°, 2°, and 3° of visual angle) and six equally spaced radii with the constraint that no two stimuli could be on adjacent intersections.

In the luminance condition, the Michelson contrast between the mean luminance of the stimuli and that of the background was 33%, with the stimuli brighter than the background. In the color condition, the stimuli were red on a green background. The two colors were set to equiluminance in a separate task in which the observers adjusted both colors so that a subjective contour, whose inducing components were red on a green background, disappeared (Cavanagh, Shioiri & MacLeod, 1987). In addition, we determined that the random texture filling the background and the stimuli effectively masked residual luminance-based information with a luminance contrast of up to 10%. The stimuli in the color condition were viewed monocularly with the dominant eye to avoid stereoscopy (Vos, 1960). The texture-defined stimuli were filled with the random-dot texture described above whereas the background was of a uniform grey of the same mean luminance as the texture. In the motion condition, the stimuli were filled with static texture and the otherwise identical background texture moved at a speed of 2 deg/sec to the left or right. The direction of motion was reversed at each trial in order to avoid motion aftereffects. Finally, binocular disparity-defined stimuli were random-dot stereograms presented as red/cyan anaglyphs and viewed through red/cyan glasses. The stimuli had a crossed disparity of .09° of visual angle which generated an apparent depth of about 10 cm in front of the screen.

Between trials the display was filled with the random texture described above except that its contrast was 25%. A fixation bull's-eye subtending 0.5° by 0.5° was present in the center of the screen.

Procedure: The experiment was run in a series of 20 blocks comprising 108 trials each. There were 10 blocks of trials for size discriminations, two for each of the five stimulus domains, one block with the large disk serving as the target and small disks as the distractors and another block with the small disk as the the target and large disks as the distractors. There were 10 similarly defined blocks for the orientation discriminations. At the beginning of a block of trials, the subject was shown the target and distractor stimuli for that block. Blocks were run in a

random order for each observer and any number of blocks could be run on the same day. Within a block of trials, the number of stimuli displayed varied randomly from 1 to 6 and on half the trials the target was present. There were 9 trials for each set size by trial type (positive or negative) combination.

Subjects initiated a trial by tilting the response lever. A warning tone then sounded and was followed by a 500 ms delay after which the stimulus display was presented. Subjects responded to the presence or absence of a target by pushing the lever to the right (present) or left (absent) with the right hand. The stimuli remained on the screen until the subject responded or until a delay of three seconds had elapsed. If no response was made during this delay, the trial was counted as an error. Subjects were instructed to respond as rapidly as possible while avoiding errors. A double warning tone sounded following an incorrect response.

RESULTS

Linear regression analyses and linear component analyses of the correct response times as a function of the number of stimuli displayed were performed on the untransformed data, separately for the two feature dimensions of size and orientation. Each experimental design involved the effects of four factors: stimulus domain (luminance, color, texture, motion or binocular disparity); target type (vertical or oblique for orientation, and large or small for size); target present or absent; and number of stimuli (1 through 6).

Mean response times for correct responses averaged across observers are shown in Figs. 1 through 4. Tables 1 through 4 show the results from the linear regression and linear component analyses .

Error rates were quite low throughout all conditions and averaged 2.23% overall. They did not correlate with error rates ($r = 0.09$), thus showing the absence of a speed-accuracy trade-off. No further analyses were performed on error rates.

Orientation Discrimination

Mean response times as a function of number of stimuli for orientation discriminations are shown in Figs. 1 and 2.

Planned analyses of the search functions relating response times to the number of stimuli displayed were performed with linear component analyses. With the oblique targets (Table 1), no

search rate was significantly greater than zero except, on positive trials, with stimuli defined in binocular disparity and, on negative trials, with stimuli defined by relative motion. In the case of relative motion, the linear regression equation for negative trials indicates a negative slope whereas the regression function for positive trials with binocular disparity stimuli indicates a positive slope.

With vertical targets (Table 2), the results were very different. With only three exceptions, all the search functions were significantly greater than zero. The exceptions occured for luminance-defined stimuli on negative trials and for stimuli defined in color on both positive and negative trials.

Are orientation features processed serially or in parallel? Our data show that the answer depends on which stimulus was the target and which the distractor. However, since the search rate on positive trials was never significantly greater than zero for oblique targets (except when defined by binocular disparity), it must be concluded that some aspect of orientation can be processed in parallel for stimuli defined by luminance, color, texture and relative motion. We base our conclusions on positive trials only because subjects will sometimes search the display more than once on negative trials and this can artificially inflate the search rate for negative responses.

The search rate asymmetry that we observed for all the stimulus domains is similar to that reported by Treisman (1985) for high-contrast, luminance-defined stimuli. She proposed that search asymmetries arise when one value on a dimension serves as a standard or reference value while other values are coded as deviations from the standard (Treisman & Gormican, 1988). The visual system appears to code the presence of a deviation as a salient feature that can be detected automatically and in parallel across the visual field, whereas the standard value gives no unique activity and is detected only through serial search with focused attention. Whatever the source of this asymmetry, it is remarkably consistent across the five domains explored in this experiment. Even for stimuli defined by binocular disparity where the search rate is significantly greater than zero for the oblique target, the search rate for the vertical target is again even greater.

Insert Figs. 1 and 2, and Tables 1 and 2
about here

Size Discrimination

Mean response times as a function of Number of stimuli for size discriminations are shown in Figs. 3 and 4.

Planned analyses of the search functions relating response times to the number of stimuli displayed were performed with linear component analyses. With the large target presented among small distractors (Table 3), the slopes on the positive trials were significantly larger than zero only for the relative motion and binocular disparity domains. On negative trials, however, all domains, except texture, gave slopes that were significantly greater than zero. With the small target presented among large distractors (Table 4), the slopes on positive trials were significantly greater than zero only for stimuli defined by luminance and binocular disparity while on negative trials, the slopes were significantly larger than zero for stimuli defined by luminance, motion, and binocular disparity.

Are size features processed serially or in parallel? The search rate on positive trials did not differ significantly from zero for at least one of the target types (large or small) in four of the five stimulus domains. Stimuli defined by binocular disparity were again the exception. Therefore some aspect of size can be processed in parallel for stimuli defined by luminance, color, texture and relative motion.

Unlike the orientation targets, the size targets gave no consistent asymmetry in the search rates for the two target types, large or small.

Insert Figs. 3 and 4, and Tables 3 and 4
about here

Comparison of positive and negative slopes

When search is serial and self-terminating, the slope on negative trials is expected to be twice the slope on positive trials. The data approximated this ratio for the conditions with significant slopes on positive trials; the mean slopes were 31.8 and 18.8 ms per item for negative and positive slopes respectively. For the remaining conditions, the results differed for the two types of targets. With targets defined by size, the negative slopes were on average much steeper than the positives (14.9 compared to 3.1 ms per item), whereas with targets defined by

orientation, the reverse was the case (-3.5 compared to 3.5 ms per item). This suggests a possible difference in the coding of orientation and size: the homogeneity of dense displays may be salient for stimuli defined by orientation, allowing a global response to the display as a whole, whereas when size is the relevant dimention, only the discrepant target is salient and its absence is, on some trials at least, confirmed by a serial check of non-target stimuli.

DISCUSSION

The main result in this experiment is that for the stimulus domains of luminance, color, texture and relative movement, search for targets defined by orientation or size could be performed in parallel. That is, for at least one of the two targets in those stimulus domains, the slope of the function relating response time to the number of stimuli did not differ significantly from zero on positive trials.

It is generally assumed that parallel processing of a given feature implies its early encoding in the visual system by specialized detectors (Treisman, 1985; Treisman & Gelade, 1980; Treisman & Souther, 1985). Following this assumption, we may conclude that, in these four visual pathways, the extraction of local structure involves the dimensions of orientation and size.

For stimuli defined by binocular disparity, discriminations of orientation and size seemed to require serial processing since there was a consistent increase of response times with the number of items displayed. At first sight, these results with stereo-defined stimuli suggest that orientation and size may not be elementary features in the binocular disparity pathway. However, this conclusion conflicts with earlier psychophysical results showing tilt and size aftereffects with binocular disparity gratings (Tyler, 1975; Cavanagh et al., 1987). It is likely, therefore, that the significant search rates with disparity-defined stimuli result from poor stimulus discriminability. Treisman & Souther (1985) showed that decreased target discriminability can lead to a change from parallel to serial processing. If parallel search depends on the detection of activity in separate feature maps coding the target but not the distractors, it should be possible only when the target activates a population of functional detectors that is clearly separable from those that respond to the distractors. When the two produce overlapping distributions of activity, attention may be narrowed to process subgroups of items or single items at a time (Treisman & Gormican, 1988). In a study of size discriminations, Treisman and Gormican (1988) also found apparently serial

processing for luminance-defined targets differing in length, with slower search rates for a size ratio of 1.23 to 1 than for a size ratio of 1.60 to 1. The present experiment used a size ratio of 1.5 to 1 in diameter (equivalent to a ratio of 2.25 to 1 in area). Thus, one explanation of our results would be that the difference between the vertical and oblique stimuli we selected for orientation discriminations and between the small and large stimuli we selected for size discriminations approached the limit of discriminability when the stimuli were presented as stereograms. If spatial resolution in the binocular disparity pathway is poor, the difference between the target and the distractors in both the size and orientation tasks may have been too small for each stimulus to activate a separate set of functional detectors (or channels) when defined in binocular disparity. Therefore, the present results need not be taken as evidence against the availability of orientation and size codes in the binocular disparity pathway; instead they may reflect an inadequate separation between the particular orientation and size channels we tested for stimuli defined by binocular disparity.

An interesting aspect in our results is the search asymmetry observed for discriminations of orientation in all the stimulus domains studied. With the exception of color- and stereo-defined stimuli, search was parallel when the target was an oblique shown among vertical distractors whereas it appeared to be serial when the target was a vertical presented among oblique distractors. With stimuli defined by color or by binocular disparity, the same search asymmetry was observed, except that the difference between search for oblique and vertical targets was only quantitative. This asymmetry between search for vertical and oblique targets is similar to that reported by Treisman (1985) and Treisman and Gormican (1988) with high-contrast luminance-defined stimuli. Models that may account for such an asymmetry have been described by Treisman and Gormican (1988).

It is interesting to note that the slopes of the search times as a function of the number of items can be flat even when the intercepts are very high. All the present search tasks gave much longer response times than those found by Treisman and Gormican (1988) for stimuli defined in the luminance domain with high constrast black lines against a white background, where the intercepts averaged between 400 and 600 ms. In the present experiment, the intercepts also varied considerably; they were much higher for stimuli defined by binocular disparity than for stimuli defined by other attributes. Tables 1 through 4 show the mean intercepts for positive and negative trials on both size and orientation targets separately for each domain. There was little difference

between color-, luminance-, texture-, and motion-defined stimuli, but stimuli defined by stereopsis were processed much more slowly.

There seem then to be two separate factors contributing to the difficulty of search tasks: (1) the ease of detecting the shape boundaries and segregating the figures from the ground within each domain; and (2) the discriminability between the features of the shapes defining the target and the distractors within each domain. The former may contribute a constant amount to the search time — a small component for high contrast luminance stimuli and a very large component for binocular disparity, with intermediate amounts for the other domains (including the small luminance contrast masked by random dot texture used in the present luminance tasks). In addition, the reduced resolution available in stimulus domains other than luminance may make the discrimination between target and distractors more difficult, thus inducing serial search rather than parallel detection for some of the stimuli.

The similarity of the results across the luminance, color, texture and motion domains is striking. The asymmetry of search in the orientation discriminations tasks is in the same direction for all stimulus domains. Codes for orientation and for size appear to be available not only for stimuli defined by luminance but also for stimuli defined by color, texture, and relative motion. Although the present results show slower search and less parallel processing in the binocular disparity domain, it is possible that with highly discriminable values on the dimensions of size and orientation, a similar pattern would emerge.

There are two possible accounts of the results in the other four domains: One is that the features tested -- differences in size and in orientation — are coded separately but in a very similar way for shapes defined by luminance, color, texture and motion boundaries. Another is that edges and discontinuities are first extracted within each of the different domains and are then combined at some higher level to give a single representation, before the shapes of three-dimensional objects are analyzed. Various functional detectors for features of shapes could then operate within this merged domain, allowing ambiguities to be resolved and misleading information discarded. Evidence from tasks measuring aftereffects of selective adaptation favor the former interpretation, suggesting that orientation and size codes are indeed duplicated throughout the visual pathways. Specifically, studies have shown that opposite tilt aftereffects can be induced simultaneously for color and for luminance stimuli (Flanagan, Cavanagh & Favreau, 1987), as can opposite size aftereffects (Favreau & Cavanagh, 1981). Such results require the duplication of size and

orientation coding at least in the color and luminance pathways. The inference would be that the information that is taken from each domain to form the final interpretation of the visual scene consists of abstracted features of edges and shapes rather than the raw edges themselves.

REFERENCES

ALLMAN, J.M. & KAAS, J.H. (1976). Representation of the visual field on the medial wall of occipital-parietal cortex in the owl monkey. *Science*, **191**, 572-575.

ARGUIN, M. & CAVANAGH, P. (1988). Parallel processing of two disjunctive targets. *Perception and Psychophysics*, **44**, 22-30.

BENTON, A.L. & HÉCAEN, H. (1970). Stereoscopic vision in patients with unilateral cerebral damage. *Neurology*, **20**, 1084-1088.

BERGEN, J.R. & JULESZ, B. (1983). Parallel versus serial processing in rapid pattern discrimination. *Nature*, **303**, 696-698.

BISHOP, P.O. (1973). Neurophysiology of binocular single vision and stereopsis. In R. Jung (Ed.), *Handbook of Sensory Physiology (pp. 256-305)*. Berlin: Springer.

BOTEZ, M.I. (1975). Two visual systems in clinical neurology: Readaptative role of the primitive system in visual agnosic patients. *European Neurology*, **13**, 101-122.

CAVANAGH, P. (1987). Reconstructing the third dimension: Interactions between color, texture, motion, binocular disparity and shape. *Computer Vision, Graphics and Image Processing*, **37**, 171-195.

CAVANAGH, P.; FLANAGAN, P. & ARGUIN, M. (1987). The coding primitives of the multiple pathways of the visual cortex. Presented at the Experimental Psychology Society, Oxford, England.

CAVANAGH, P.; SHIOIRI, S. & MacLEOD, D.J.A. (1987). Is the achromatic form pathway based on luminance or brightness? *Investigative Ophthalmology and Visual Science Supp.*, **28**, 362.

CARMON, A. & BECHTOLDT, H.P. (1969). Dominance of the right cerebral hemisphere for stereopsis. *Neuropsychologia*, **7**, 29-40.

DAMASIO, A.; YAMADA, T.; DAMASIO, H.; CORBETT, J. & McKEE, J. (1980). Central achromatopsia: Behavioral, anatomic, and physiologic aspects. *Neurology*, **30**, 1064-1071.

DeVALOIS, R.L. & DeVALOIS, K.K. (1975). Neural coding of color. In E.C. Carterette & M.P. Friedman (Eds.), *Handbook of Perception Vol. 5 (pp. 117-166)*. Academic

Press: New York.

DOBBINS, A.; ZUCKER, S.W. & CYNADER, M.S. (1987). Endstopped neurons in the visual cortex as a substrate for calculating curvature. *Nature*, **329**, 438-441.

EGETH H.; JONIDES, J. & WALL, S. (1972). Parallel processing of multi-element displays. *Cognitive Psychology*, **3**, 674-698.

FAVREAU, O.E. & CAVANAGH, P. (1981). Color and luminance: Independent frequency shifts. *Science*, **212**, 831-832.

FLANAGAN, P.; CAVANAGH, P. & FAVREAU, O.E. (1987). Orientation is processed in chromatic channels. *Journal of the Optical Society of America A*, **4**, P115.

GIBSON, J.J. (1950). *The Perception of the Visual World.* Boston: Houghton Mifflin.

GOURAS, P. & EGGERS, H.M. (1982). Retinal responses to color contrast. *Investigative Ophtalmology and Visual Science Supp.*, **22**, 176.

HAMMOND, P. & MacKAY, D.M. (1977). Differential responsiveness of simple and complex cells in cat striate cortex to visual texture. *Experimental Brain Research*, **30**, 275-296.

HAMMOND, P. & SMITH, A.T. (1982). On the sensitivity of complex cells in feline striate cortex to relative motion. *Experimental Brain Research*, **47**, 457-460.

HUBEL, D.H. & WIESEL, T.N. (1965). Receptive fields and functional architecture in two nonstriate visual areas (18 and 19) of the cat. *Journal of Neurophysiology*, **28**, 229-289.

HUBEL, D.H. & WIESEL, T.N. (1968). Receptive fields and functional architecture of monkey striate cortex. *Journal of Physiology*, **195**, 215-243.

JULESZ, B. (1971). *Foundations of Cyclopean Perception*, Chicago: University of Chicago Press.

JULESZ, B. (1981). Textons, the elements of texture perception and their interactions. *Nature*, **290**, 91-97.

LENNIE, P.; SCLAR, G. & KRAUSKOPF, J. (1985). Chromatic sensitivities of neurons in striate cortex of macaque. *Investigative Ophtalmology and Visual Sciences Supp.* , **26**, 8.

LIVINGSTONE, M.S. & HUBEL, D.H. (1987). Specificity of cortico-cortical connections in monkey visual system. *Nature*, **304**, 531-534.

MAUNSELL, J.H.R. & NEWSOME, W.T. (1987). Visual processing in monkey extrastriate

cortex. *Annual Review of Neurosciences*, **10**, 363-401.

MICHAEL, C.R. (1978). Colour sensitive complex cells in monkey striate cortex. *Journal of Neurophysiology*, **41**, 1250-1266.

MOVSHON, J.A.; THOMPSON, I.D. & TOLHURST, D.J. (1978). Spatial and temporal contrast sensitivity of neurones in areas 17 and 18 of the cat's visual cortex. *Journal of Physiology*, **282**, 101-120.

NEISSER, U. (1963). Decision time without reaction time: Experiments in visual scanning. *American Journal of Psychology*, **76**, 376-385.

NOTHDURFT, H.C. & LI, C.Y. (1985). Texture discrimination: Representation of orientation and luminance differences in cells of the cat striate cortex. *Vision Research*, **25**, 99-113.

POGGIO, G.F. & FISHER, B. (1977). Binocular interaction and depth sensitivity in striate and prestriate cortex of behaving rhesus monkey. *Journal of Neurophysiology*, **40**, 1392-1405.

POGGIO, G.F.; MOTTER, B.C.; SQUATRITO, S. & TROTTER, Y. (1985). Responses of neurons in visual cortex (V1 and V2) of the alert macaque to dynamic random-dot stereograms. *Vision Research*, **25**, 397-406.

ROVAMO, J.; HYVÄRINEN, L. & HARI, R. (1982). Human vision without luminance contrast system: Selective recovery of the red-green colour-contrast system from acquired blindness. *Documenta Ophthalmologica Proceedings Series*, **33**, 457-466.

THORELL, L.G.; De VALOIS, R.L. & ALBRECHT, G. (1984). Spatial mapping of monkey V1 cells with pure color and luminance stimuli. *Vision Research*, **24**, 751-769.

TREISMAN, A. (1985). Preattentive processing in vision.*Computer Vision, Graphics and Image Processing*, **31**, 156-177.

TREISMAN, A. & GELADE, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, **12**, 97-136.

TREISMAN, A. & GORMICAN, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review*, **95**, 15-48.

TREISMAN, A. & SOUTHER, J. (1985). Search asymmetry: A diagnostic for preattentive processing of separable features. *Journal of Experimental Psychology: General*, **114**, 285-310.

TREISMAN, A., SYKES, M., GELADE, G. (1977). Selective attention and stimulus integration. In S. Dornic (Ed.), *Attention and Performance VI (pp. 333-361)*. Hillsdale, NJ: Erlbaum.

TYLER, C.W. (1975). Stereoscopic tilt and size aftereffects. *Perception*, **4**, 187-192.

VAN ESSEN, D.C. (1985). Functional organization of primate visual cortex. In A. Peters & E.G. Jones (Eds.), *Cerebral Cortex*, New York: Plenum Publishing, 3: 259-329.

VAN ESSEN, D.C. & MAUNSELL, J.H.R. (1983). Hierarchical organization and functional streams in the visual cortex. *Trends in Neuroscience*, **6**, 370-375.

VON DER HEYDT, R.; PETERHAUS, E. & BAUMGARTNER, G. (1984). Illusory contours and cortical neuron responses. *Science*, **224**, 1260-1262.

VOS, J.J. (1960). Some new aspects of color stereoscopy. *Journal of the Optical Society of America*, **50**, 578-590.

ZEKI, S.M. (1973). Color coding in rhesus monkey prestriate cortex. *Brain Research*, **53**, 422-427.

ZEKI, S.M. (1978). Functional specialization and binocular interaction in the visual areas of the rhesus monkey. *Nature*, **274**, 423-428.

ZIHL, J.; VON CRAMON, D. & MAI, N. (1983). Selective disturbance of movement vision after bilateral brain damage. *Brain*, **106**, 313-340.

FIGURE CAPTIONS

FIG. 1. Mean response times as a function of the Number of stimuli for (a) positive trials and (b) negative trials, in which the target is an oblique bar and distractors are vertical bars. Regression lines are shown for each stimulus domain.

FIG. 2. Mean response times as a function of the Number of stimuli for (a) positive trials and (b) negative trials, in which the target is a vertical bar and distractors are oblique bars. Regression lines are shown for each stimulus domain.

FIG. 3. Mean response times as a function of the Number of stimuli for (a) positive trials and (b) negative trials, in which the target is a large disk and distractors are small disks. Regression lines are shown for each stimulus domain.

FIG. 4. Mean response times as a function of the Number of stimuli for (a) positive trials and (b) negative trials, in which the target is a small disk and distractors are large disks. Regression lines are shown for each stimulus domain.

TABLES

Table 1. Regression coefficients and linear components (df = 1, 35) for the Number of stimuli factor with search for an oblique target among vertical distractors.

Positive trials

Stimulus domain	Regression function	Linear Component F	p<
Luminance	y = 853.3 + 7.8x	1.96	ns
Color	y = 856.6 - 1.9x	0.18	ns
Texture	y = 856.6 + 3.3x	1.35	ns
Motion	y = 866.6 + 3.6x	1.53	ns
Binocular disparity	y = 1092.5 +11.4x	4.44	.05

Negauve trials

Stimulus domain	Regression function	Linear Component F	p<
Luminance	y = 943.0 - 5.8x	0.93	ns
Color	y = 883.8 - 2.8x	0.89	ns
Texture	y = 952.2 - 7.5x	2.12	ns
Motion	y = 952.2 - 7.5x	5.66	.025
Binocular disparity	y = 1442.4 +11.9x	.52	ns

Table 2. Regression coefficients and linear components (df = 1, 35) for the Number of stimuli factor with search for a vertical target among oblique distractors.

Positive trials

Stimulus domain	Regression function	Linear Component F	Linear Component p<
Luminance	y = 858.6 +17.6x	12.81	.005
Color	y = 900.3 + 4.9x	1.48	ns
Texture	y = 888.2 +10.8x	6.12	.025
Motion	y = 922.8 +14.6x	9.71	.005
Binocular disparity	y = 1058.4 +47.4x	24.37	.001

Negative trials

Stimulus domain	Regression function	Linear Component F	Linear Component p<
Luminance	y = 948.2 - 0.9x	0.02	ns
Color	y = 921.3 + 5.9x	2.34	ns
Texture	y = 893.3 +14.1x	5.71	.025
Motion	y = 1029.5 +15.1x	9.21	.005
Binocular disparity	y = 1279.8 +80.6x	49.07	.001

Table 3. Regression coefficients and linear components (df = 1, 35) for the Number of stimuli factor with search for a large target among small distractors.

Positive trials

Stimulus domain	Regression function	Linear Component F	p<
Luminance	y = 928.0 + 1.4x	0.04	ns
Color	y = 893.9 + 4.9x	1.47	ns
Texture	y = 917.5 + 2.8x	0.44	ns
Motion	y = 932.2 +11.4x	7.07	.025
Binocular disparity	y = 1062.0 +14.2x	7.71	.01

Negative trials

Stimulus domain	Regression function	Linear Component F	p<
Luminance	y = 973.2 +13.0x	5.71	.025
Color	y = 929.1 +14.9x	6.82	.025
Texture	y = 988.0 + 8.3x	1.31	ns
Motion	y = 995.7 +26.2x	12.69	.005
Binocular disparity	y = 1144.3 +46.2x	22.04	.001

Table 4. Regression coefficients and linear components (df = 1, 35) for the Number of stimuli factor with search for a small target among large distractors.

Positive trials

Stimulus domain	Regression function	Linear Component F	p<
Luminance	y = 916.4 +11.1x	5.50	.05
Color	y = 943.0 - 1.7x	0.08	ns
Texture	y = 911.2 + 3.7x	0.67	ns
Motion	y = 987.9 + 7.5x	1.84	ns
Binocular disparity	y = 1032.7 +30.9x	35.59	.001

Negative trials

Stimulus domain	Regression function	Linear Component F	p<
Luminance	y = 925.1 +32.8x	11.80	.005
Color	y = 960.3 +12.2x	3.09	ns
Texture	y = 968.5 + 4.3x	0.71	ns
Motion	y = 973.5 +36.5x	19.91	.001
Binocular disparity	y = 1181.6 +60.2x	38.42	.001

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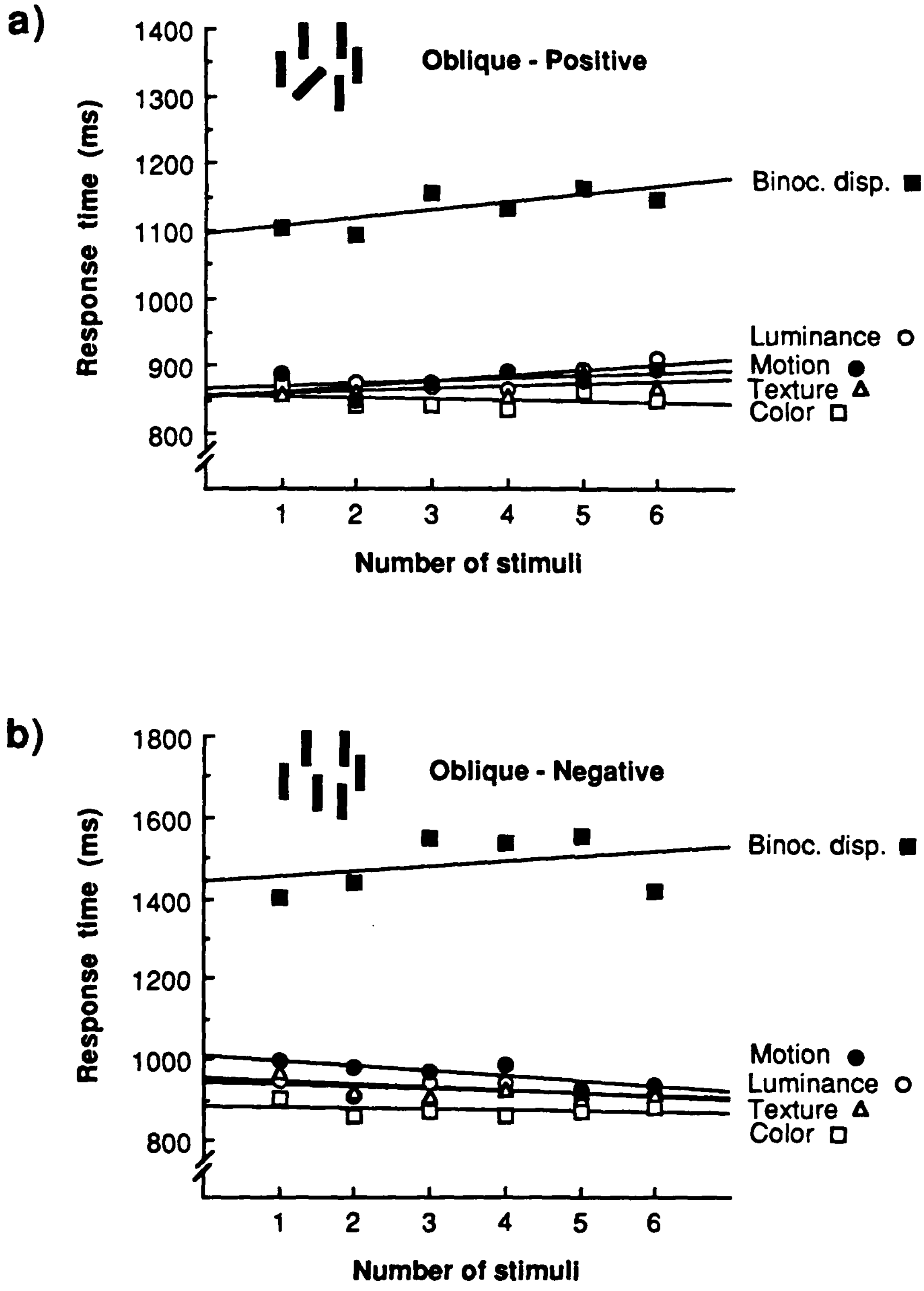
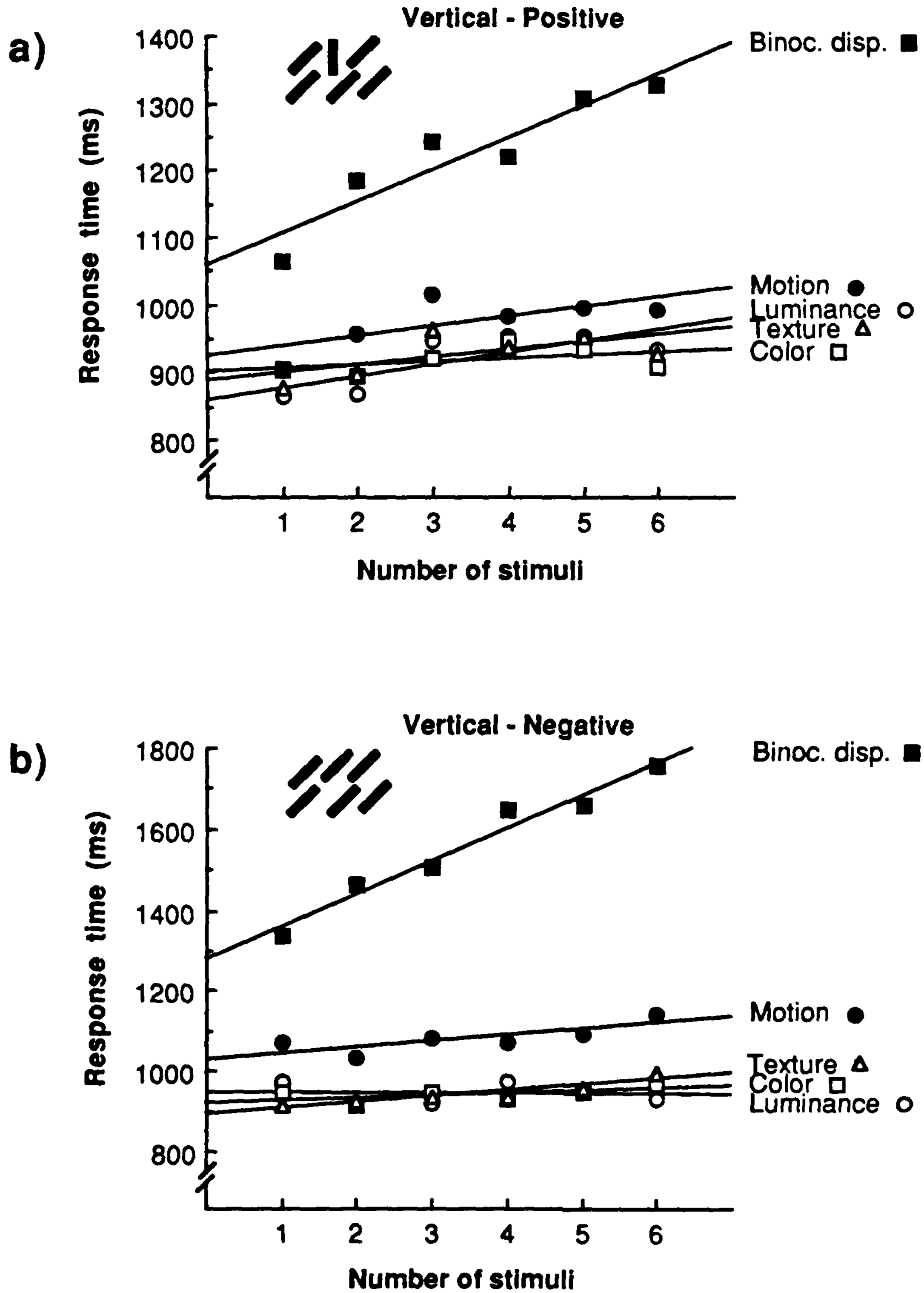

a)
Oblique - Positive
Response time (ms)
1400
1300
1200
1100
1000
900
800
Binoc. disp.
Luminance
Motion
Texture
Color
1
2
3
4
5
6
Number of stimuli
b)
Oblique - Negative
Response time (ms)
1800
1600
1400
1200
1000
800
Binoc. disp.
Motion
Luminance
Texture
Color
1
2
3
4
5
6
Number of stimuli

FIG. 1



a)
Vertical - Positive
Response time (ms)
1400
1300
1200
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Binoc. disp.
Motion
Luminance
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Color
1
2
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6
Number of stimuli
b)
Vertical - Negative
Response time (ms)
1800
1600
1400
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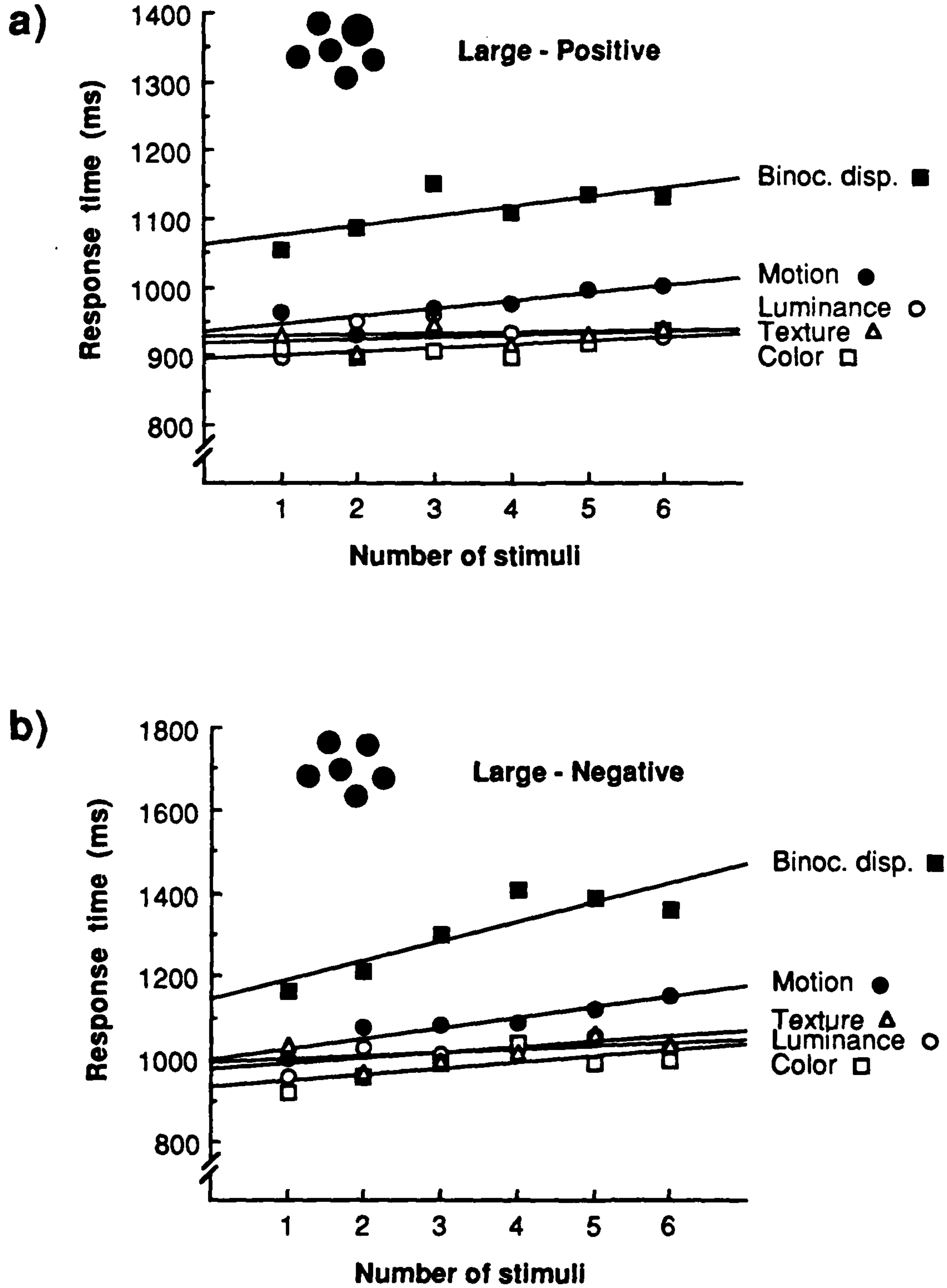
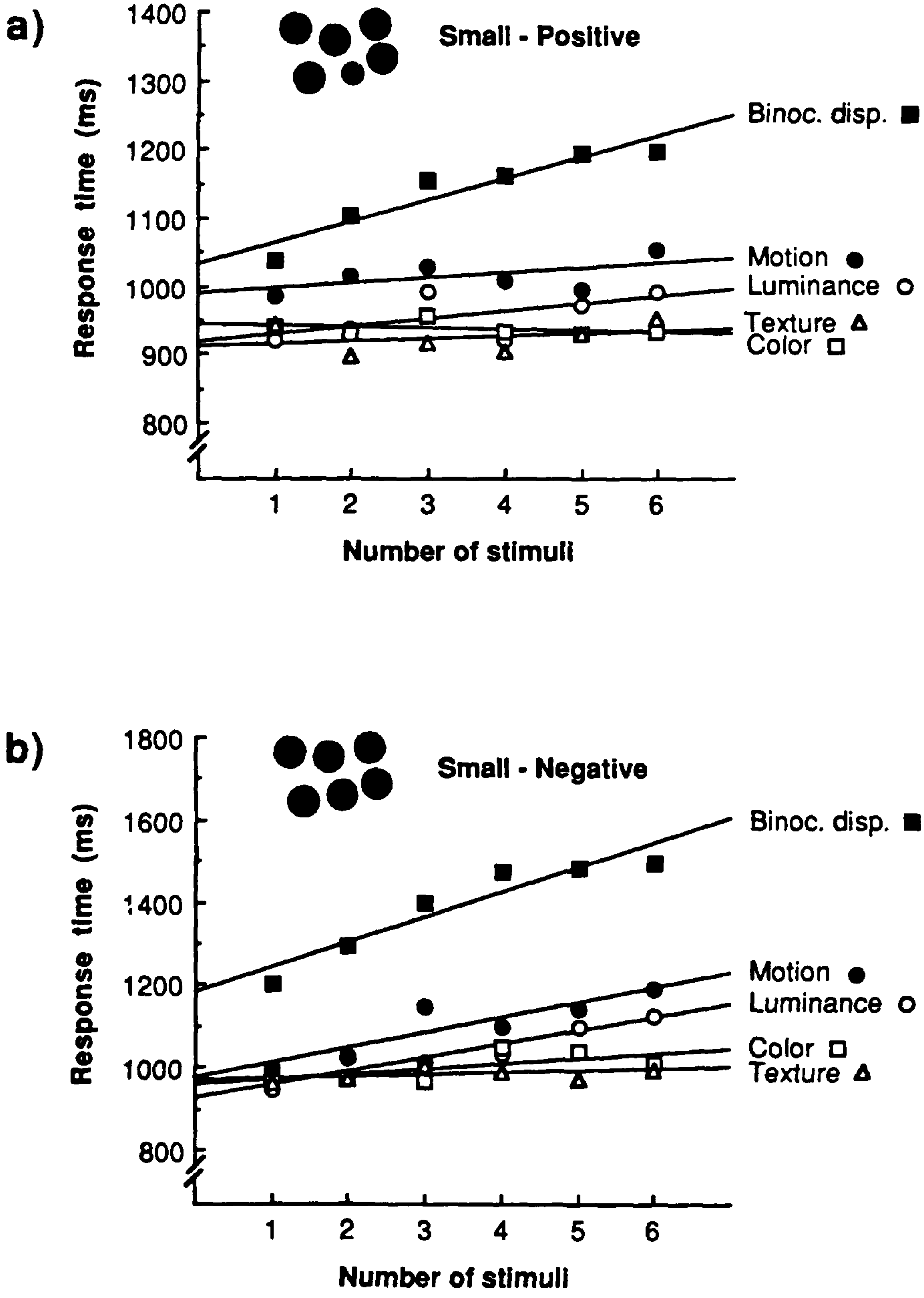
1000
800
Binoc. disp.
Motion
Texture
Color
Luminance
1
2
3
4
5
6
Number of stimuli

FIG. 2



a)
Large - Positive
Response time (ms)
1400
1300
1200
1100
1000
900
800
Binoc. disp.
Motion
Luminance
Texture
Color
1
2
3
4
5
6
Number of stimuli
b)
Large - Negative
Response time (ms)
1800
1600
1400
1200
1000
800
Binoc. disp.
Motion
Texture
Luminance
Color
1
2
3
4
5
6
Number of stimuli

FIG. 3



a)
Small - Positive
Response time (ms)
1400
1300
1200
1100
1000
900
800
1
2
3
4
5
6
Number of stimuli
Binoc. disp.
Motion
Luminance
Texture
Color
b)
Small - Negative
Response time (ms)
1800
1600
1400
1200
1000
800
1
2
3
4
5
6
Number of stimuli
Binoc. disp.
Motion
Luminance
Color
Texture

FIG. 4

Implicit and Explicit Memory for Visual Patterns

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Running Head: MEMORY FOR VISUAL PATTERNS

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Abstract

The present study investigated implicit and explicit memory for novel, nonverbal stimuli. Implicit memory was assessed by a speeded perception task and explicit memory by a four alternative forced-choice recognition task. Tests were given at intervals from thirty minutes to forty days. Performance measures in the two tasks showed stochastic independence and the results suggest that a single exposure of a novel, nonverbal stimulus is sufficient to establish a representation in memory that is capable of supporting long-lived perceptual priming, and that shows little change with additional exposures. In contrast, recognition memory was affected by the number of exposures and showed significant decay over the same delay. Finally, a specific occurrence of a previously studied item could be retrieved from explicit memory, but did not affect the accuracy of perception in the implicit memory test. The results extend the domain of experimental dissociations to include explicit and implicit memory for novel, nonverbal stimuli.

Introduction

It is now well established that performance on explicit and implicit memory tests can show dissociations. These terms, which were first introduced by Graf and Schacter (1985), are meant only as descriptive labels and thus imply no assumptions about underlying processes or structures. Explicit memory reflects conscious recollection of a previous experience. It can be assessed by standard tests of recognition and recall in which subjects deliberately select or retrieve previously studied items. In contrast, implicit memory tests are designed to tap memory without requiring the subject to engage in conscious recollection. Implicit memory is inferred from repetition priming effects in tasks such as word-identification, word-fragment completion and perceptual recognition with masking or brief exposures. When performance on these tests is better for previously presented material than for new material, the facilitation is said to be mediated by implicit memory.

Measures of performance in implicit and explicit memory have been shown in some tasks to be stochastically independent (Tulving, Schacter and Stark 1982, Eich, 1984; Jacoby and Witherspoon, 1982; Schacter Harbluk, and McLachlan, 1984) in the sense that performance in the two tasks is uncorrelated at the level of individual items. Correct recall of a particular item in the explicit memory test does not imply priming of the same item in the implicit memory test, and vice versa. The two memory measures have

also shown functional independence in the effects of other variables such as delay, (Tulving et al., 1982), level of processing (Jacoby and Dallas, 1981), and retroactive and proactive interference (Graf and Schacter, 1987). Perhaps most impressive are the dissociations shown by amnesic patients. Various neurological disorders can lead to extremely poor performance on tests of explicit memory combined with near normal performance on tests of implicit memory (e.g., Cohen and Squire, 1980, Graf, Shimamura and Squire 1985; Graf, Squire and Mandler, 1984; Jacoby and Witherspoon, 1982, Schacter 1985b, Cermak, Talbot, Chandler and Wolbarst, 1985, Nissen, Cohen and Corkin, 1981). Thus, the data from both amnesic patients and normal subjects suggest two fundamentally different forms of memory.

A number of theories have been proposed to account for these dissociations. Kinsbourne and Wood (1975) first explained the results with amnesic patients in terms of Tulving's distinction between episodic and semantic memory: amnesic patients were thought to have lost the ability to lay down (or retrieve) episodic traces of autobiographical events, but had preserved semantic memory. Repetition priming could be attributed to persisting activation of nodes or pathways in a semantic or conceptual recognition network. The stochastic and functional independence of priming and recognition measures found in normal subjects was attributed to the same distinction between semantic and episodic memory systems by Tulving (1983). A somewhat different dichotomy between procedural and declarative memory has been used to explain the dissociations

by Cohen and Squire (1980).

Several researchers reject any account in terms of separate memory systems, and suggest instead that different aspects of the same memory traces are used in the different explicit and implicit memory tasks. For example, Jacoby (1983a, 1983b) explains both repetition priming and recognition or recall within an exemplar model of episodic memory, suggesting that all tests depend on the retrieval of prior processing episodes. Both Jacoby and Kolers (1979) emphasize that performance at retrieval depends critically on the relationship between the study and retrieval environments. The independence of priming and recognition are explained by the different aspects of the memorized information that are used to perform the tasks required. Implicit and explicit memory differences have also been attributed to the different retrieval strategies they normally evoke -- a conscious, intentional strategy for recognition contrasting with and automatic, incidental retrieval in perceptual identification (Mandler, 1988).

The evidence distinguishing these accounts is still inconclusive, although recent findings have cast doubt on the idea that the semantic-episodic separation can cover all the observed phenomena. The account that attributes repetition priming to the persisting activation of nodes in semantic memory seems most apt when the stimuli to be memorized are words. Yet Kolers (1979), Jacoby and Hayman, (1987) and Masson, (1986) showed that priming effects for words are largest when the physical characteristics of the stimuli are kept constant across study and test situations.

The specificity suggests that details of the particular encoding are retained and revived in tasks that draw on implicit as well as explicit memory.

Explicit and implicit memory dissociations have usually been studied with familiar verbal material, but there have been a few reports of similar results with pictures of common objects. In the earliest studies, Warrington and Weiskrantz (1968, 1970) tested amnesic patients and normal subjects in the identification of incomplete drawings. There was a clear dissociation between the amnesics' good performance with partial information cues and their impaired performance on the explicit memory tasks (recognition and free recall). Carroll, Byrne and Kirsner (1985) and Mitchell and Brown (1988) measured repetition priming and recognition for pictures in normal subjects. Carroll et al. found functional independence in response to different delays. Mitchell and Brown found both stochastic and functional independence. Repetition priming in their experiment lasted up to 6 weeks, while recognition performance dropped significantly over the same period. Although these stimuli were nonverbal, they were nevertheless familiar and would lend themselves quite readily to verbal labelling. The priming effects, like those found for words, might therefore be attributed to persisting activation of pre-existing semantic memory representations, independently of episodic or contextual information.

Recently, however, two findings have cast more doubt on the generality of this account. Feustel, Salasoo and Shiffrin (1983)

and Salasoo, Shiffrin and Feustel (1985) demonstrated repetition priming for non-words as well as words, and Graf and Schacter reported a series of studies showing priming effects for novel paired associates such as WINDOW-REASON, (Graf and Schacter, 1985; Schacter, 1986a, Graf and Schacter, 1987). Presumably neither the non-words nor the associations were previously represented in semantic memory. The results therefore raise problems for the traditional account, and seem to fit better with an exemplar model in which the same episodic traces contribute to implicit as well as explicit memory. Feustel, Salasoo and Shiffrin (1983) suggest that episodic traces can be accessed by different cues in the two kinds of tasks: recognition depends on contextual cues which fade with time, while identification uses physical cues and relations, which remain more constant across time delays. They see word identification as resulting from " a race between episodic and semantic traces or from some synergistic interaction between the two."

The priming of novel paired associates reported by Graf and Schacter (1985) also raises problems for a semantic memory account, since the arbitrary associations should not be represented there. Priming was obtained for these novel paired associates only when the subjects had engaged in elaborative processing likely to link the words during acquisition. Schacter and Graf (1986b), like Jacoby (1983) and Kolers (1975, 1976), explain these results in terms of episodic representations rather than by the activation of pre-existing semantic networks. They postulate the existence of

two kinds of priming: a short-lived activation of semantic memory nodes when familiar units like single words are involved, and a longer-lived availability of episodic representations for new associations. The latter are formed only when the subject has engaged in elaborative processing at acquisition.

The findings with novel paired associates and non-words raise difficulties for the semantic memory account. However, both still use familiar verbal material -- words or letters -- as the stimuli, albeit in novel combinations. The present experiment was designed to extend this research by exploring possible dissociations between implicit and explicit measures with novel, nonverbal visual stimuli. We chose arbitrary line patterns that could have no pre-existing memory representations. Implicit memory was inferred from perceptual priming with brief masked presentations and explicit memory was measured by forced choice recognition. If priming could be demonstrated with these stimuli, it would be difficult to attribute it to persisting activation in pre-existing nodes or pathways. Any functional dissociations or stochastic independence between priming and recognition would presumably require some explanation other than the separation of semantic from episodic memory traces.

Gabrieli, Milberg, Keane, and Corkin (submitted) recently reported a similar study. Their subjects were presented with five dots from nine possible dots in a 3x3 dot matrix and were asked to draw any figure that connected the dots. The figures they drew were used as a baseline condition. Later, the same subjects were

asked to copy particular target figures onto a piece of paper. They were then re-presented with the five dot stimuli and asked to draw the first pattern that came to mind. They found that control subjects and the well-documented amnesic patient, H.M., drew target figures more often than they had in the baseline condition. Gabrieli et al. interpreted this as a demonstration of priming of nonverbal material in both normal subjects and the amnesic patient H.M.. One possible objection is that the subjects were asked to draw the first pattern that came to mind. Since the task had no correct answer, the normal subjects may well have drawn on explicit memory for the target figures to solve the task. Gabrieli et al. did not compare the priming performance with explicit memory measures; nor did they look for dissociations in the effects of other factors like delay or repetition.

The experiment described below was designed to investigate a series of issues regarding memory for these novel visual patterns. (1) Would stochastic independence be found between explicit memory (assessed by a four alternative recognition test) and implicit memory (assessed by repetition priming in a perception test)? Subjects studied a list of patterns similar to those used by Gabrieli et al. (see Figure 1). In the recognition test, they were asked to choose among four figures, presented in each of the four corners of the screen, which one they remembered studying. The distractors were chosen to be as similar to the target as possible. They differed at most in two of the five lines. We adopted a new method for testing implicit memory that allowed us to measure

performance without requiring a verbal response and with no demands on explicit memory. Subjects were shown both studied and new patterns, briefly presented and immediately masked at a stimulus-onset-asynchrony (SOA) at which they could correctly reproduce only 50-60% of the patterns. They were required to draw each briefly presented pattern on a sheet of paper with pre-drawn 3x3 dot matrices. Since speed was emphasized, and there was a correct response, we believed that this perceptual task would discourage the use of explicit memory for earlier study trials more effectively than the task used by Gabrieli et al. The measure of implicit memory was the difference in accuracy between previously studied figures and new figures, a measure we will refer to as perceptual priming. We looked for stochastic independence between the recognition and the perception test for each subject with each pattern.

Insert Figure 1 about here

---

(2) Would there be a functional dissociation between explicit and implicit memory using delay as the independent variable, as previously observed with verbal material? We tested different groups of subjects in both explicit and implicit memory tasks at different delays after presentation and after different numbers of presentations. Three groups of subjects were tested- an "Immediate" a "Delay" group and a "Single Presentation" group. The "Delay" and the "Immediate groups viewed the stimuli once and completed an

initial set of memory tests. The "Delay" group then viewed the same stimuli four additional times and returned for testing one week later. The "Immediate" group left and returned the next day to view the stimuli four additional times. This study period was followed immediately by the memory tests. The "Immediate" group also had an additional test session one week after this session, allowing us to compare immediate recognition with recognition after a week's delay within the same group of subjects and to see the effect of the additional immediate test when both groups were tested a week after presentation. Finally, both groups were also tested again a month later. The third group of subjects, the "Single Presentation" group, participated in two test sessions only. On the first day they followed the same procedure as the "Immediate" group and in the second session a week later, they followed the same procedure as the "Delay" group. This group was used to measure the strength and durability of the priming effect after just a single exposure, and, by comparison with the "Delay" group, to assess the effects of four additional exposures.

(3) Finally, we looked for a possible dissociation between implicit and explicit memory in discriminating a single additional presentation of a subset of previously learned patterns -- a direct test of episodic memory. In this test, the discrimination for both explicit recognition and perceptual priming was between learned patterns shown once again during the test session ("Old-Old" patterns) and learned patterns that had not been re-presented within the test session ("Old-New" patterns). Past research using

familiar stimuli like words has typically measured subjects' ability to discriminate stimuli presented in the experiment from other stimuli which were also familiar, (e.g. Tulving et al., 1982, Jacoby and Dallas, 1981). The procedure used here is analogous because it examines whether people can discriminate recently seen (Old-Old) patterns from other familiar stimuli (Old-New) on the basis of just one additional exposure.

In order to obtain meaningful measures of stochastic independence, a number of conditions must be met. Independence could result simply from random performance on one or both tests. On the other hand, complete dependence could result from perfect performance on each test separately, even if retrieval was from completely independent memory systems. For a sensitive test of stochastic independence, performance should be in the mid-range between chance and perfect performance. As a check on the sensitivity, it is important to show that performance on two replications of the <u>same</u> memory test does show dependence in memory for the same item on successive trials.

Secondly, as Shimamura (1985) points out, the test procedures themselves could introduce either dependence or independence. Since the two tasks must test the same learned items, the first task could affect performance on the second, even if the memory representations would otherwise have been independent. In fact, in the best known study performed by Tulving et al. (1982), stochastic independence was found only when recognition was tested before word-fragment completion. When the tests were given in the

reverse order, a correlation was observed. Tulving et al. (1982) suggested that the fragment completion task allowed an extra study opportunity for the correctly completed words. Order effects are also possible when the recognition test is given first. In Tulving et al.'s (1982) study, accuracy on the word-fragment completion task was higher when it followed than when it preceded the recognition test, regardless of whether the word was correctly recognized. Shimamura argues that the prior presentation of the target words mixed with distractors in the recognition test may dilute any correlation that would otherwise exist between the two tasks; in this case stochastic independence could be an artifact resulting from the test procedure.

In an attempt to assess and to minimize these interactions, each of our subjects was given three memory tests in each session. Either the recognition test or the perception test was repeated to allow a measure of the amount of dependence between identical tests. The order of the three tests was counterbalanced across subjects.

Method.

Stimuli. Two hundred fifty patterns were used. The patterns were generated from a 3x3 dot matrix. They consisted of five connected lines joining dots in the matrix. The patterns were generated in a pseudo-random fashion. First a random number generator was used to designate which sets of points to connect. As more patterns were generated, a program was used to check and eliminate pattern repetitions. The experiment also employed a mask which consisted

of all the possible lines that could be drawn in the 3x3 matrix. 50 patterns were used only to assess the threshold for the perception test. Two study lists containing different sets of 50 patterns were generated and were counterbalanced across subjects. The remaining 100 patterns were used as distractors.

The patterns were presented *in green on* black by means of a PDP-11/73 computer connected to an HP 1345A vector graphics system. The vector display screen measured 14 x 7.67 cm., and was surrounded by a black cardboard mask with a rectangle of the same size cut from it. The patterns measured 2.4 x 2.4 cm. The subject was seated approximately 57 cm. from the screen, so that each pattern subtended approximately 2.4 degrees of visual angle. The displays of four patterns used in the recognition tests were arranged in the four quadrants of an imaginary square measuring 7.62 cm x 7.62 cm.

Design. All subjects participated in both types of memory tests: perception and recognition memory. Test order, test comparisons and study list were varied between subjects. Type of test was varied within subjects. Each subject was given three memory tests within the same session: two identical tests of the same items (both recognition or both perception) and one different test (either perception or recognition). Four test orders were used R_1-R_2-P (i.e., recognition, recognition, perception), P-R_1-R_2, P_1-P_2-R, and R-P_1-P_2. The second memory test in each case was used in two separate measures of stochastic independence, one with the first test and one with the third. For example, for test order R_1-

R_2 -P stochastic independence would be measured between R_1 and R_2 and between R_2 and P.

Subjects. Thirty-two subjects participated in the experiment. They were undergraduate and graduate students at the University of California at Berkeley who volunteered to take part and were paid $5/hour. Sixteen subjects participated in the "Delay" condition, eight in the "Immediate" condition and eight in the "Single Presentation" group. They were randomly assigned to the combinations of study list x test order.

Procedure. There were two study lists of 50 patterns each. Half the subjects in each group studied one list and half the subjects studied the other. For each group, the patterns not studied were used together with another 100 patterns, as distractors for the recognition memory test and as new patterns in the perception test. On each day, the same 150 distractors were used for recognition memory but a different 50 patterns chosen from the 150 distractors for the recognition test were used in the perception test.

A number of different tasks were given in different combinations to different groups, as shown in Table 1. The experiment consisted of four sessions for the "Delay" group, five for the "Immediate" group and two for the "Single Presentation" group. Each subject received the same test order in every session. A detailed description of the procedures within each phase follows.

Insert Table 1 about here

Threshold determination

Before each perception test, a threshold exposure duration was determined separately for each subject. Fifty patterns not used in the main experiment were presented in order to assess the stimulus-onset-asynchrony (SOA) at which each subject could reproduce about 50% of the patterns completely correctly. The patterns were presented briefly, immediately followed by the mask consisting of all possible lines that could be drawn in the matrix. After each pattern was presented, subjects were asked immediately to draw the pattern they had seen by connecting the relevant lines in the dot matrices provided on sheets of paper. After the subject completed a block of trials, the answers were immediately scored. A pattern was considered correct only if all its component lines were correct. Twenty patterns, each presented twice, were used initially to find a range of exposure durations at which each subject could draw 40-60% of the patterns correctly. Thirty new patterns were then presented three times at six different randomly mixed SOA's between pattern and mask (spaced at 20 ms each). The SOA at which performance in the final block was between 50 and 60% correct was chosen for the perception test that would be used to measure implicit memory.

Initial Study

Subjects were given 50 new patterns to study (not used in the

threshold determination task). The 50 patterns were presented as three sequences of 17, 17, and 16 patterns each. This was done to facilitate learning of these unfamiliar stimuli. On each trial, a fixation point appeared in the center of the screen for 250 ms followed by a pattern which appeared for 3 seconds. Subjects were allowed 7 seconds to rehearse the pattern when it was no longer on the screen before the next trial began. After each sequence of 16 or 17 patterns, the subject was given the three memory tests for that subset of patterns, (see below for procedure).

Repeated Study

The 50 patterns were presented in a single sequence for one second each. The list was repeated three more times in the same way, making four complete presentations.

Memory Tests

The recognition test was a four alternative forced-choice test. On each trial one studied pattern was presented with three new patterns randomly placed in the four corners of the screen. Subjects were asked explicitly to choose which of the four stimuli they had studied. The patterns remained on the screen until the subject responded. When they had decided which figure was the target, they indicated their decision by hitting the response key that corresponded to that screen location. The set of patterns was tested once or twice, depending on whether the subject was assigned two recognition or two perception tests. The second test presented the same items in a different order.

In the perception test, each studied pattern was presented

singly, followed by the mask at the predetermined SOA. An equal number of new patterns was presented, randomly intermixed in the sequence. Subjects were instructed to draw what they saw. They were not informed that any of the patterns were previously studied. If they inquired about the purpose of the task, they were told it was a filler task to control the length of delay between studying the stimuli and the recognition test. The drawing was self-paced; subjects were instructed to hit any key to go onto the next trial after they had completed the pattern. A priming effect was measured by comparing performance on "old" and on "new" patterns within the test. In each set of memory tests except those contained in the initial study phase, all fifty patterns were tested in a single sequence. This was repeated three times to give two recognition tests and one perception test or two perception tests and one recognition test for each subject.

Episodic memory study and tests (Old-Old vs. Old-New patterns)

Subjects studied 25 of the 50 patterns once more for 2 seconds each, with a 250 ms inter-stimulus interval. These patterns will be referred to as Old-Old patterns. The other 25 patterns will be referred to as Old-New patterns. The perception test consisted of 50 patterns -- 25 Old-Old patterns and 25 Old-New ones, randomly mixed. The recognition test was modified to a two-alternative forced-choice task, instead of a four alternative task, in which the subject chose between an Old-Old and an Old-New pattern on each trial.

These study and test procedures were given at different times

and in different combinations to the three groups of subjects as specified in Table 1.

Results.

Table 2 and Figure 2 show the mean percentage of patterns drawn completely correctly in the perception test and the mean percentages correctly recognized in each condition. Note that the absolute levels of performance in perception cannot be directly compared across sessions, since the SOA was separately determined for each session. For example, the "Single Presentation" group showed lower perceptual accuracy on Day 8, but this may be due in part to the fact that the SOA's averaged 28.5 ms less on Day 8 than on Day 1. The aim was to ensure that performance would be in the right range, avoiding ceiling and floor effects. In fact, a general skill learning was observed as subjects SOA's scores dropped about 70 ms, from the first to the last session, for subjects in the Delay and Immediate groups and 35 ms for subjects in the Single Presentation group. However, the critical measure of implicit memory is the priming effect (the difference between old and new patterns within each session).

Insert Table 2 and Figure 2 about here

Perceptual Priming effect. The perceptual priming scores were combined for all subjects regardless of test order which did not significantly effect priming performance. The differences between "Old" and "New" patterns were compared for subjects who received

the perception test first with those who received it second or third, for all the subjects for Day 1, and for subjects in the "Immediate" and "Delay" groups for the week and the month delay conditions. The means were 8.13, 8.67, and 7.00 for perception first and 9.08, 9.75 and 8.00 for perception second for the Day 1, week and month sessions respectively. None of the differences were significant.

A t-test revealed significant amounts of priming for all sessions except the Old-Old vs. Old-New session (day 3 for the Immediate group; day 9 for the Delay group).

Table 3 shows the effects of delay. It gives the mean differences in the amount of priming (percentage of old patterns correctly reproduced minus the percentage of new patterns correctly reproduced) at different delay intervals. There were no significant effects of delay on priming for any group between any of the test sessions. A between-groups comparison of the "Immediate" group tested in the same session after the main study with multiple exposures (day 2) and the "Delay" group tested after an eight day delay also showed no significant difference in priming, (see Figure 3).

The effect of four additional study trials on priming is shown by the difference in the performance of the "Immediate group" on Day 1 and on Day 2 (a difference of 4.6%, n.s.).

Insert Table 3 and Figure 3 about here

<u>Recognition.</u> The recognition scores were also combined for all subjects, since test order again had no effect on performance. Accuracy was compared for subjects who were tested on recognition before and after perception, pooling scores in the same way as for the perception test for Day 1, and the week and the month delay sessions. The means were 72.37, 74.83, and 70.66 for recognition first, and 76.80, 69.33, and 67.33 for recognition second for the Day 1, week and month sessions respectively. None of the differences were significant.

The effect of delay on recognition performance is also shown in Table 3. There was a significant drop in accuracy for the "Immediate" group between the test on day 2 (after the multiple exposures) and the test one month later ($t(7) = 3.72$, $p < .01$), and a significant drop between day 10 and one month later $t(7) = 6.26$, $p < .01$. However, the drop in performance between day 2 and day 10 was not significant ($t(7) = .35$, $p = .74$). For the "Delay" group there was no significant drop in recognition performance between the test on day 8 and the test after a month's delay ($t(15) = .69$, $p = .5$,). However, a between-groups comparison showed a highly significant difference between the "Immediate" group's test on the same day as the study phase and the "Delay" group's test after one week. The "Immediate" group, had a mean recognition score of 86.3% correct, whereas the "Delay" group had a mean of only 65.0% ($t(22) = 3.76$, $p < .001$, see Figure 3). The "Single Presentation" group also showed a significant drop in recognition performance after a

week's delay (*t*(7)=4.16 *p* <.005. This effect is shown graphically in Figure 4. Thus, the week's delay caused a drop in performance except when the learning was initially tested immediately after the four repeated study trials.

The effect of four additional exposures on recognition is shown by the increase of 12% for the "Immediate" group between Day 1 and Day 2 (*t*(7)=2.62 *p* < .03).

Insert Figures 4 and 5 about here

Stochastic independence. Each subject's scores were entered into a 2x2 contingency table for each test session (as shown in Figure 5). The log of the cross product ratio was calculated for each subject who had an expected value of at least 3 in each cell. The cross-product ratio is the maximum likelihood estimate of an interaction between two attributes in a 2 x 2 table. (Bishop et al. (1975) The log of the cross-product ratio is preferred to chi-square because it is symmetric about zero, ranging from $-\infty$ to $+\infty$. The log of the cross-product ratio was calculated for each subject for each test session, between the performance on the perception test and the performance on the recognition test, and also between the two identical tests, whether these were of perception or of recognition. These numbers were then entered into a t-test for the group of subjects to see if they differed significantly from zero (i.e., from independence.) The scores for the tests after a single exposure in the first session and for the tests after a one month delay were combined for the "Immediate" and "Delay" groups, since

the conditions were the same for the two groups and the means did not differ significantly. The N=12 because each subject only participated in half of the possible test orders. The results of this test are presented in Table 4.

Insert Table 4 about here

Table 4 indicates that on all days identical tests showed dependence whereas the different tests showed stochastic independence. (It should be noted, however, that after a one week delay, R-P and P-R comparisons (for the delay group) were close to being dependent.) There was no reason to check for stochastic independence in the Old-Old vs. Old-New session because no priming difference was obtained on this test. Also, stochastic independence was not computed for the Immediate group on day 2 because the expected values for 13 test comparisons were less than 3 in one of the cells in the independence table.[1]

Discussion.

The experiment suggests a number of conclusions on the nature of visual memory for nonverbal patterns: (1) Visual memory shows a remarkable plasticity, allowing a single 3 second exposure to prime later perception as strongly after a week as after a few minutes delay (Single Presentation Group). Further, a single 3 second exposure plus four additional 1 second exposures was enough to sustain a priming effect for up to a month. (2) Tests of implicit and explicit memory show stochastic independence even

after a single exposure to novel visual patterns. The independence continues after four more presentations and after delays of a week and a month. (3) There is a functional dissociation between the effects of delay on implicit and explicit memory for visual stimuli, just as there is for verbal stimuli. (4) There is also a functional dissociation between explicit and implicit memory in the effects of a particular occurrence of a previously studied pattern. We will discuss each of these findings in turn.

(1) Repetition priming in the perception of novel visual patterns:

The experiment clearly demonstrates repetition priming for novel visual patterns. The fact that it occurred at almost full strength after a single exposure rules out an account in terms of persisting activation of pre-existing memory representations, whether nodes in a semantic network (e.g. logogens, Morton, 1969) or procedures that are used to perform familiar skills. It poses a challenge for connectionist learning models, which would normally require repeated trials to adjust connection weights and establish a stable, repeatable pattern of response. The record of a single perceptual experience must be preserved and retrieved to facilitate perception on subsequent presentations.

Note, however, that the comparisons in both priming and recognition tests were with completely novel patterns only in the first recognition or priming tests. After that, the same 150 distractor patterns were re-used in subsequent tests, so that they were eventually seen as many as twelve times (by the R_1 - R_2 - P and P -R_1 -R_2 subjects in the Immediate Group). Since the same

distractors were used in the recognition and in the priming tests, any accrued familiarity was matched across tests. It is possible, however, that the implicit priming did build up over successive presentations of the "Old" patterns, and that the increase would have become apparent if the comparison had been with completely novel patterns.

(2) Stochastic independence of repetition priming and recognition:

Perception and forced-choice recognition showed stochastic independence when the same individual was tested on the same previously presented pattern in the same test session. Before drawing any inferences from this result, however, it was important to test for correlations between repeated tests within the same task. Stochastic independence could be found simply because the data were too noisy, or because performance was too poor or too good to allow the necessary range of variation across items. Neither account seems to apply to the present results. The repeated tests with the same measures all showed significant dependence, as would be expected if they reflect the same underlying representations and procedures.

The stochastic independence we obtained with novel, nonverbal stimuli is surprising, given that the priming cannot be attributed to activation in long-term semantic memory nodes. Both implicit and explicit memory measures should depend on episodic memory traces; yet the independence suggests that different information is retrieved by the two tasks. With novel, meaningless visual patterns, it is less easy than with or words or familiar objects

to appeal to differences between data-driven and conceptually-driven codes or to differences in the relationship between study and retrieval contexts. Some other explanation for the independence is needed. We return to this problem below.

(3) Effects of Delay:

The difference in the accuracy with which "Old" and "New" patterns could be perceived and reproduced was strikingly constant across sessions. Repetition priming was as strong after one exposure (with lists of 17) as after four additional exposures (with lists of 50). It was also as strong after one month as after one week's delay or no delay. The results suggest that a single exposure of a novel nonverbal stimulus forms a memory representation sufficient to produce implicit priming that remains equally effective for at least one month.

In contrast, recognition performance showed a significant drop across the same period of time (for the "Immediate" group between day 10 and day 40 and day 2 and day 40, for the "Single Exposure" group between day 1 and day 8 and for the between-groups comparison of day 2 "Immediate" to day 8 "Delay".) For the "Delay" group, the main loss in accuracy occurred during the first week. They showed no further drop in performance between one week and one month. The difference between the two groups may be due to their different study and test conditions: Subjects in the "Delay" condition studied the stimuli five times in one session, followed by a test one week later, whereas subjects in the "Immediate" group studied the stimuli in a more distributed way (once during the first

session and four times during the second session.) Distributed study is generally more effective than massed study (e.g. McGeoch 1942; Peterson, Wampler, Kirkpatrick and Saltzman, 1963; Underwood, 1970; Jacoby, 1978; Glenberg, 1979). In addition, the "Immediate" group were tested once after the initial four exposure study period. This gave them three additional exposures to the patterns (one in each of the memory tests they participated in) and may have helped to consolidate the learning.

The results from the "Single Exposure" group and from the between-groups comparison of "Immediate" and "Delay" subjects suggest that a significant drop in recognition performance can occur after a one week delay without any accompanying decrease in priming performance. Thus repetition priming seems to reflect a more durable memory trace than recognition, suggesting a functional dissociation between explicit and implicit memory.

Similar results have been reported with verbal material. Tulving et al, 1982 found that priming, as reflected by performance on word-fragment completion tasks, lasted up to a week and Sloman, Hayman, Ohta, Law and Tulving, 1988 found that after an initial 5 minute phase of rapid forgetting, priming in word-fragment completion showed a very slow rate of decay, persisting up to 16 months after study. There has, however been considerable variation across experiments in the persistence of priming over time. Graf et al. (1984) suggest several variables that may affect its duration. Among them are word frequency and the number of response alternatives (e.g., word-fragments with one possible

solution may show longer priming effects than those with many solutions).

Long-lasting priming has also been found with meaningless stimuli (such as non-words) and with skilled performance such as mirror-reading or solving the Tower of Hanoi problem. Salasoo et al. (1985) demonstrated repetition priming effects for nonwords that lasted up to a year. The repetition priming effects appeared to be more persistent for nonwords than for words. McClelland and Rumelhart (1986) suggested that the less often the stimuli are encountered in everyday life, the longer the priming effects may last. The close tie between the experimental contexts during training and testing may cause the long-lived priming.

Studies of skill acquisition are often treated separately from studies of repetition-priming. It is assumed that skills are generalizable to all material handled by the same operations, whereas repetition priming effects are by definition specific to the re-presentation of the identical stimulus material. Both these assumptions can be questioned: Graf et al. 1985 found that repetition priming can also occur between semantic associates both in normal controls and in amnesic patients. Kolers (1979) showed greater priming for the identical words than for different words in tests of reading speed with inverted, rotated or otherwise transformed words. He found that subjects performed better on familiar than unfamiliar text, and showed additional benefit if the text reappeared in the same orientation as during study. This effect lasted up to a year. Kolers suggested that the procedures

learned during study are retained, and when the same stimuli are presented later, the same learned procedures are contacted again. The closer the match between encoding and test, the better performance will be. Again, the uniqueness of the stimulus material may be responsible for the longevity of the priming effect.

It seems that the uniqueness, novelty, and specificity of the visual details of the stimuli all contribute to priming of long duration. All these qualities were present with the line figures used in the present study. The stimuli were novel, nonsense stick figures that subjects were unlikely to encounter in everyday life. Their visual characteristics were undoubtedly important because they were meaningless and had no other distinguishing properties or associations. It is therefore not surprising that they gave rise to robust and long-lived priming effects.

(4) Memory for a particular occurrence:

Most studies of memory, both explicit and implicit, measure retention of particular occurrences of previously familiar items, whether words, sentences or nameable pictures. The present experiment required subjects both to form an initial representation of each stimulus and to distinguish it from other similar patterns (the distractors in the recognition test.) In addition, in one session of the present experiment we explicitly tested the effects of a single specific exposure, by asking subjects to discriminate patterns that they had seen one additional time in that particular session from other patterns they had seen only on previous days. This is analogous to presenting a word list of familiar words and

asking subjects to remember which of a larger set of familiar words they had seen in that particular list.

In the session contrasting Old-Old with Old-New patterns, subjects did about as well on the explicit memory test of recognition as they did in the previous session testing recognition of familiar among unfamiliar patterns. On the other hand, they showed little or no perceptual priming from this one extra exposure. Thus, this test of strictly episodic memory showed a strong dissociation between the explicit recognition performance of 81% accuracy and the small and nonsignificant priming difference between Old-Old and Old-New patterns. An additional exposure is apparently distinctively coded in an explicit memory trace, but not in the representations that support implicit memory for nonverbal stimuli. In the recognition test, the "Old-Old" patterns could be distinguished from the "Old-New" patterns in either of two respects: increased strength due to recency and to the additional exposure and/or associations to current context. There was no increase in priming, suggesting that the additional exposure had its effect on recognition not by increasing the strength of the memory trace but by setting up new contextual associations. Jacoby (1983a) suggested that if the context is salient, it will influence implicit as well as explicit memory. He varied the proportion of items in common to both study and test list and found that implicit memory increased with the number of shared items. However, in the present experiment, the contextual associations that supported explicit recognition had no effect on implicit memory.

Conclusions

What then, are the characteristics of the visual memory representations suggested by the priming data on the one hand and by the recognition data on the other? Do they force an interpretation in terms of separate memory systems, or could they be reconciled in an account based on a single memory system? The repetition priming results suggest an all-or-nothing effect. The critical factor is whether a single representation has been formed or not -- whether an episodic trace or exemplar has been laid down. Adding more exemplars, or strengthening the first, gives little additional benefit. Nor does the passage of time do much to weaken the representation or to reduce access to it when the stimulus is presented in a degraded form. The recognition results, on the other hand, suggest a substantial improvement in explicit memory with additional presentations. Moreover, subjects can distinguish one additional presentation from five prior presentations, suggesting that individual exemplars (or at least, the most recent) must have some unique characteristics allowing their retrieval in a recognition test, although they produce no additional priming in perception. Finally, the representation(s) used in recognition tests either decay or become less accessible as time passes.

The contrasting effects of repetition and of delay on implicit and explicit memory may give further clues to the underlying processes. Let us consider three possible effects of repetition: (1) The same single trace is strengthened by each repetition; (2)

additional links are formed between a single trace and a representation of the context; (3) a new exemplar is formed in memory for every new occurrence of a stimulus. On the first view, it would be puzzling that priming shows neither much benefit of repetition nor much loss with time. It would also be difficult to explain the stochastic independence we found between the tests of recognition and of perceptual priming. On the second view, repetition would leave priming unchanged, since the subject is not required to retrieve the context, but recognition would clearly benefit from the formation of new associations to the experimental context. The third view is the most radical; it adopts the exemplar model of episodic traces (Jacoby, 1983a, 1983b, 1984; Whittlesea, 1987) To account for the relative invariance we found in priming, we suggest that when a new stimulus is presented for perception it is automatically matched to one and only one previous matching exemplar before the perceptual processing is completed (Kahneman, Treisman, and Gibbs, 1988, in preparation). The effect is an all-or-nothing benefit in perception for the repeated relative to a novel stimulus.

The same automatic matching must occur in the forced-choice recognition test which also re-presents the original pattern. However the "perceptual fluency" that results from matching to a single exemplar may in some circumstances be (Jacoby 1983a) insufficient to select the old pattern among the new distractors. Explicit recognition requires subjects to retrieve memory information which distinguishes one pattern from another;

perceptual fluency may not provide the distinctive information in a test in which all four items are easily visible. To mediate recognition, traces of earlier presentations must be not only retrieved but in some way labelled as belonging to the study list. In the course of a recognition trial, (unlike the brief exposures of the perception trials), there is time to retrieve more than one exemplar (if more than one has been stored). The number of exemplars available can then affect the confidence of the judgment that the same pattern has been seen on one or more previous occasions.

This account has been framed as a single exemplar model. We note, however, that it can be further elaborated to include a distinction between types and tokens that would reconcile our findings with the semantic-episodic framework. A single occurrence may suffice to set up a representation of a new stimulus as a "type" to which later presentations are automatically matched in perception tasks. Both the first and the later presentations are also recorded as particular tokens or exemplars of the type, and it is these that mediate explicit memory for their occurrence at a particular time and in a particular context. Further research will be needed to distinguish which of these accounts is closest to the truth.

References

Bishop, Y., Feinberg, S. E. and Holland, P. W. (1975). Discrete Multivariate Analysis: Theory and Practice. MIT Press.

Carroll, M. Byrne, B. and Kirsner, K. (1985). Autobiographical memory and perceptual leaning: A developmental study using picture recognition, naming latency and perceptual identification. Memory and Cognition, 13, 273-279.

Cermak, L. S., Talbot, N., Chandler, K., and Wolbarst, L. R. (1985). The perceptual priming phenomenon in amnesia. Neuropsychologia, 23, 615-622.

Cohen, N. J., and Squire, L. R. (1980). Preserved learning and retention of pattern analyzing skills in amnesia: Dissociation of knowing how and knowing that. Science, 1210, 207-210.

Eich, E. (1984). Memory for unattended events: Remembering with and without awareness. Memory and Cognition, 12, 105-111.

Feustel, T. C., Shiffrin, R. M., Salasoo, A. (1983). Episodic and lexical contributions to the repetition effect in word identification. Journal of Experimental Psychology: General, 112, 309-346.

Gabrieli, J. D., Milberg, W., Keane, M. M. and Corkin, S. (submitted to Neuropsychologia) Intact priming of patterns despite impaired memory.

Glenberg, A. M. (1979). Component levels theory of the effects of spacing of repetition on recall and recognition. Memory and Cognition, 7, 95-112.

Graf, P. and Schacter, D. L., (1985). Implicit and explicit memory for new associations in normal and amnesic subjects. Journal of Experimental Psychology: Learning, Memory, and Cognition, 11, 501-518.

Graf, P. and Schacter, D. L., (1987). Selective effects of interference on implicit and explicit memory for new associations. Journal of Experimental Psychology: Learning, Memory and Cognition, 13, 45-53.

Graf, P. Squire, L. R., and Mandler, G. (1984). The information that amnesic patients do not forget. Journal of Experimental Psychology: Learning, Memory and Cognition, 10, 164-178.

Graf, P., Shimamura, A. P. and Squire, L. R. (1985). Priming across modalities and priming across category levels: Extending the domain of preserved function in amnesia. Journal of Experimental Psychology: Learning, Memory and Cognition, 11, 386-396.

Jacoby, L. L. (1983a). Perceptual enhancement: Persistent effects of an experience. Journal of Experimental Psychology: Learning, Memory and Cognition, 9, 21-38.

Jacoby, L. L. (1983b). Remembering the data: Analyzing interactive processes in reading. Journal of Verbal Learning and Verbal Behavior, 22, 485-508.

Jacoby, L. L. (1984). Incidental versus intentional retrieval: Remembering and awareness as separate issues. In L. R. Squire and N. Butters (Eds.) Neuropsychology of Memory. New York: Guilford Press.

Jacoby, L. L. and Witherspoon, D.(1982). Remembering without

awareness. Canadian Journal of Psychology, 32, 300-324.

Jacoby, L. L. and Hayman, C. A. G. (1987). Specific visual transfer in word identification. Journal of Experimental Psychology: Learning, Memory and Cognition, 13, 456-463.

Kahneman, D., Treisman, A. and Gibbs, B. (in preparation).

Kinsbourne, M. and Wood, F. (1975). Short-term memory and the amnesic syndrome. In D. Deutsch and J. A. Deutsch (Eds.), Short Term Memory. New York: Academic Press.

Kolers, P. A. (1975). Memorial consequences of automatized encoding. Journal of Experimental Psychology: Human Learning and Memory, 2, 554-565.

Kolers, P. A. (1976). Reading a year later. Journal of Experimental Psychology: Human Learning and Memory, 2, 554-565.

Kolers, P. A. (1979). A pattern-analyzing basis of recognition. In L. S. Cermak and F. I. M. Craik (Eds.) Levels of Processing in Human Memory. Hillsdale, N. J.: Erlbaum.

Kolers, P. A. and Roediger, H. L. III. (1984). Procedures of mind. Journal of Verbal Learning and Verbal Behavior, 23, 425-444.

McClelland, J. L. and Rumelhart, D. E., (1986) A distributed model of human learning and memory. In James. L. McClelland, David E. Rumelhart, and the PDP Research Group. Parallel Distributed Processing: Explorations in the Microstructure of Cognition, Vol. 2, Psychological and Biological Models. Cambridge, MA: MIT Press.

McGeoch, J. A. (1942). The Psychology of Human Learning. New

York: Longmans, Green.

Mandler, G. (1988). Memory:Conscious and unconscious. In P. R. Solomon, G. R. Goethals, C. M. Kelley, and B. R. Stephens (Eds.), Memory -- An Interdisciplinary Approach. New York: Springer Verlag.

Masson, M. E. J. (1986). Identification of typographically transformed words: Insttance-based skill acquisition. Journal of Experimental Psychology: Learning, Memory and Cognition, 12, 479-488.

Mitchell, D. S., and Brown, A. S. (1988. Persistent repetition priming in picture naming and its dissociation from recognition memory. Journal of Experimental Psychology: Learning, Memory and Cognition, 14, 213-222.

Morton, J. (1969). The interaction of information in word recognition. Psychological Review, 76, 165-178.

Nissen, M. J., Cohen, N. J., and Corkin, S. (1981). The amnesic patient H.M.: Learning and retention of perceptual skills. Society of Neuroscience Abstracts, 7, 235.

Peterson, L. R., Wampler, R., Kirkpatrick, M., and Saltzman, D. (1963). Effect of spacing of presentations on retention of a paired associate over short intervals. Journal of Experimental Psychology, 66, 206-209.

Salasoo, A., Shiffrin, R. M., and Feustel, T. C. (1985). Building permanent codes: Codification and repetition effects in word identification. Journal of Experimental Psychology: General, 114, 50-77.

Schacter, D. L. (1985a). Multiple forms of memory in humans

and animals. In N. M. Weinberger, McGaugh, J., Lynch, G. (Eds.) Memory systems of the brain: Animal and human cognitive processes. New York: The Guilford Press.

Schacter, D. L. (1985b). Priming of old and new knowledge in amnesic patients and normal subjects. Annals of the New York Academy of Sciences, 44-53.

Schacter, D. L. and Graf, P. (1986a). Preserved learning in amnesic patients: Perspectives from research on direct priming. Journal of Clinical and Experimental Psychology, 8, 727-743.

Schacter, D. L. and Graf, P. (1986b). Effects of elaborative processing on implicit and explicit memory for new associations. Journal of Experimental Psychology: Learning, Memory and Cognition, 12, 432-444.

Schacter, D. L. and Graf, P. (in press). Modality specificity of implicit memory new associations. Journal of Experimental Psychology: Learning, Memory and Cognition.

Schacter, D. L., Harbluk, J. L., and McLachlan, D. R. (1984). Retrieval without recollection: An experimental analysis of source amnesia. Journal of Verbal Learning and Verbal Behavior, 23, 593-611.

Shimamura, A. P., (1985). Problems with the finding of stochastic independence as evidence for multiple memory systems. Bulletin of Psychonomic Science, 6, 506-508.

Sloman, S. A., Hayman, C. A. G., Ohta, N., Law, J. and Tulving, E. (1988). Forgetting in primed fragment completion. Journal of Experimental Psychology: Learning, Memory and Cognition,

14, 223-239.

Tulving, E. (1983). Elements of Episodic Memory, Oxford: Clarendon Press.

Tulving, E. (1985). How many memory systems are there? American Psychologist, 40, 385-398.

Tulving, E., Schacter, D. L., and Stark. H. (1982). Priming effects of word-fragment completion are independent of recognition memory. Journal of Experimental Psychology: Learning, Memory and Cognition, 8, 336-342.

Underwood, B. J. (1970). A breakdown of the total-time law in free-recall learning. Journal of Verbal Learning and Verbal Behavior, 9, 573-580.

Warrington, E. K. and Weiskrantz, L. (1968). New methods of testing long-term retention with special reference to amnesic patients. Nature, 217, 972-974.

Warrington, E. K. and Weiskrantz, L. (1970). Amnesic syndrome: Consolidation od retrieval? Nature, 228, 628-630.

Whittlesea, B. W. A. (1987). Preservation of experiences in representation of general knowledge. Journal of Experimental Psychology: Learning, Memory and Cognition, 13, 3-17.

Author Notes

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Footnotes

1. Recall that since each subject participated in three memory tests, two scores could be obtained per subject. This is why there are more test comparisons than subjects.

2. The higher and more highly significant the figures, the higher the dependence.

Table 1

Sequence of study and test procedures for each group of subjects

	"Immediate" (N=8)	"Delay" (N=16)	"Single Presentation" (N=8)
Day 1	Threshold for SOA Initial study once (17, 17, 16) Memory Tests __________	Threshold for SOA Initial study once (17, 17, 16) Memory Tests Repeated Study (four presentations)	Threshold for SOA Initial study once (17, 17, 16) Memory Tests __________
Day 2	Threshold for SOA Repeated study (four presentations) Memory Tests	__________	__________
Day 3	Study half the items Threshold for SOA Episodic tests of Old-Old vs. Old-New	__________	__________
Day 8	__________	Threshold for SOA Memory Tests	Threshold for SOA Memory Tests
Day 10	Threshold for SOA Memory Tests	Episodic Study (half list once again) Threshold for SOA Episodic tests of Old-Old vs. Old-New	__________
Day 40	Threshold for SOA Memory Tests	Threshold for SOA Memory Tests	__________

Table 2

Percent correct perception and recognition after different delays.

	"Immediate" group			"Delayed" group			"Single presentation" group		
	N = 8			N = 16			N = 8		
	Perception		Recognition	Perception		Recognition	Perception		Recognition
	Old	New		Old	New		Old	New	
Day 1	67.5	51.7	74.3	59.5	43.6	72.8	56.0	41.0	77.3
Priming	15.8			15.9			15.0		
t =	7.81			11.37			3.95		
p <	.001			.001			.005		
Day 2	63.2	42.8	86.3						
Priming	20.4								
t =	7.77								
p <	.001								
Day 8				60.2	41.9	65.4	44.8	33.8	55.8
Priming				18.3			11.0		
t =				10.00			3.18		
p <				.001			.05		
Day 10	57.0	36.0	85.5						
Priming	21.0								
t =	7.78								
p <	.001								
Day 40	45.2	27.8	73.0	51.0	35.4	67.0			
Priming	17.4			15.6					
t =	5.84			7.67					
p <	.001			.001					
Old-Old vs. Old-New	(Day 3)			(Day 10)					
	57.0	54.4	82.2	65.6	64.7	80.3			
Priming	2.6			0.9					
t =	.78			.36					
p <	.46			.72					

Table 3

Mean % drop in priming and recognition as a function of delay interval

	"Immediate" group		"Delay" group		"Single exposure" group
	Day 2-10	Day 10-40	Day 2-40	Day 8-40	Day 1-8
		Perception			
Priming	-1.6 $t(7) = .13$, n.s.	3.6 $t(7) = .96$, n.s.	3.0 $t(7) = .73$, n.s.	2.4 $t(15) = .98$ n.s	4.0 $t = .61$ n.s.
		Recognition			
Accuracy	.8 $t(7) = .35$ n.s	12.5 $t(7) = 6.16$ $p < .01$	13.3 $t(7) = 3.72$ $p < .01$	-2.0 $t(15) = .69$ n.s.	21.5 $t = 4.06$ $p < .005$

Table 4[2]

Results of tests for stochastic independence (for all subjects with expected values of at least 3 in each cell).

	Both Groups Day 1 (N=12)	Delayed Group Day 8 (N=8)	Immed. Group Day 10 (N=4)	Both Groups Day 40 (N=12)	Single Pres. Day 1 (N=4)	Single Pres. Day 8 (N=4)
r-p						
t	1.63	2.27	1.31	1.07	.86	1.39
p =	.13	.06	.28	.30	.45	.26
p-r						
t	.88	2.00	.14	.29	.67	.68
p =	.39	.09	.64	.28	.55	.54
r-r						
t	7.04	5.43	5.44	11.68	4.59	18.99
p <	.001	.001	.01	.001	.02	.001
p-p						
t	4.29	5.26	4.71	6.66	10.43	4.52
p <	.001	.001	.02	.02	.002	.02

Figure Captions

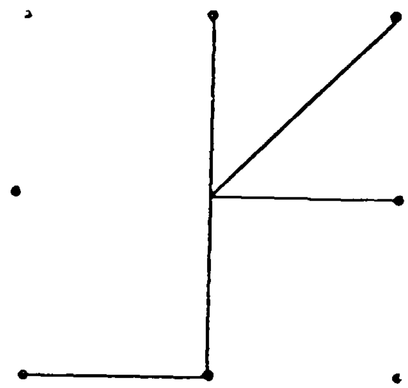
Figure 1. Example of a pattern used in the experiment.

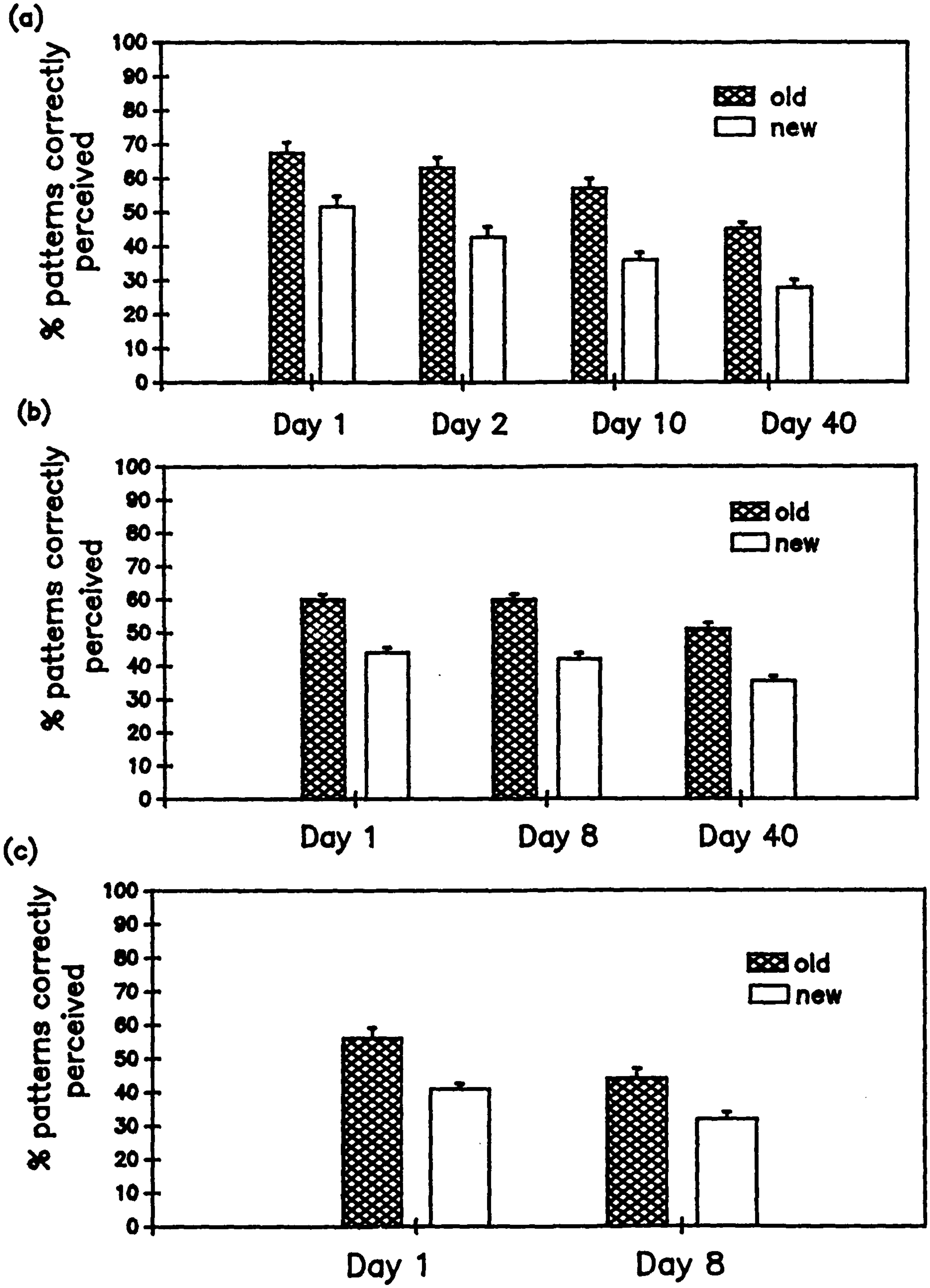
Figure 2. Priming effect for the three subject groups: (a) Immediate Group; (b) Delay Group; (c) Single Presentation Group. (Error bars are standard error of the mean).

Figure 3. The effect of a one week delay on perception and recognition performance measured between groups. (Error bars are standard error of the mean).

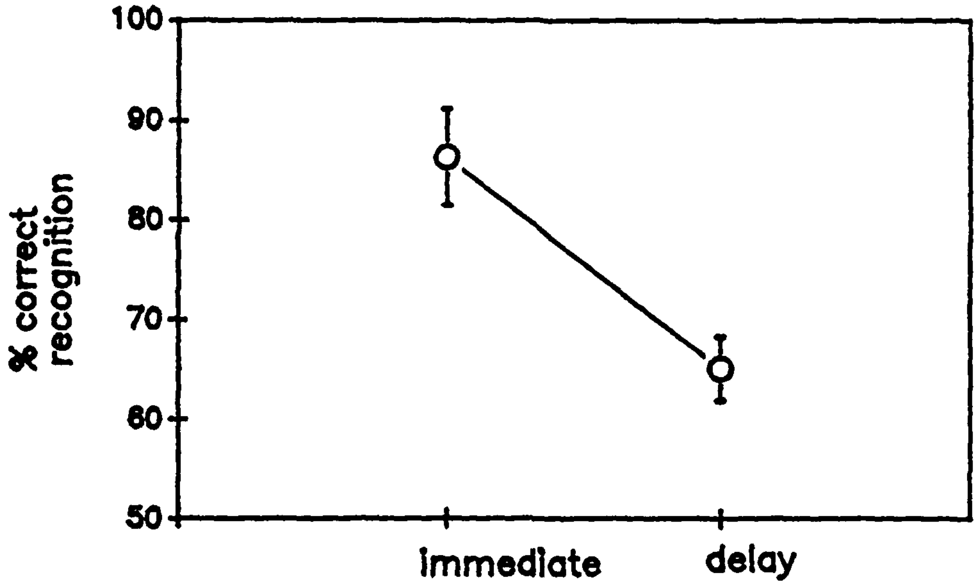
Figure 4. The effect of a one week delay on perception and recognition performance for the Single Presentation Group. (Error bars are standard error of the mean).

Figure 5. An example of a contingency table used to calculate the log of the cross product ratio for each subject.

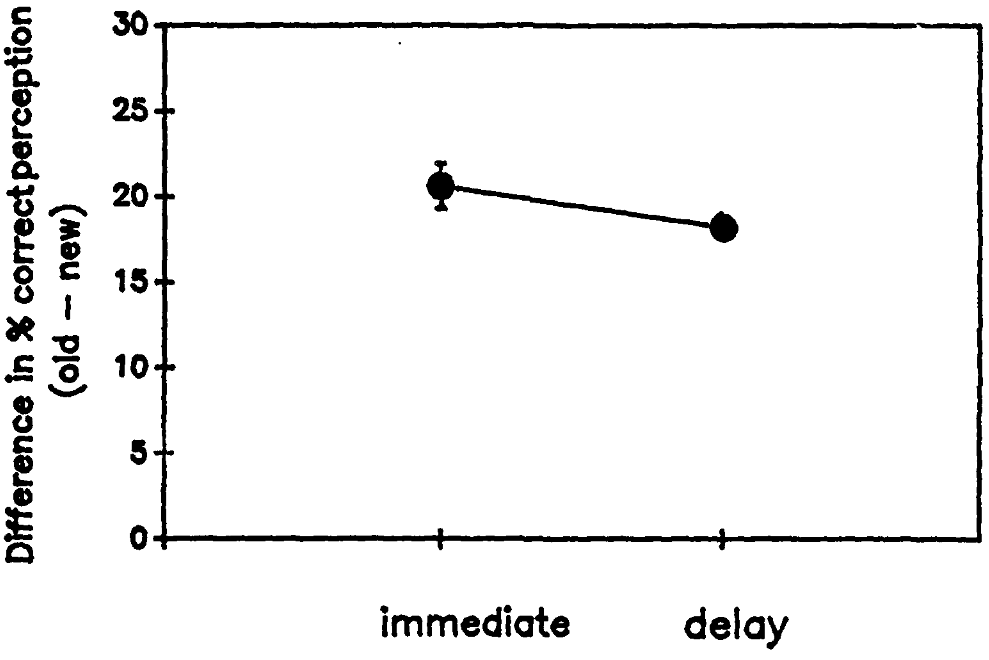




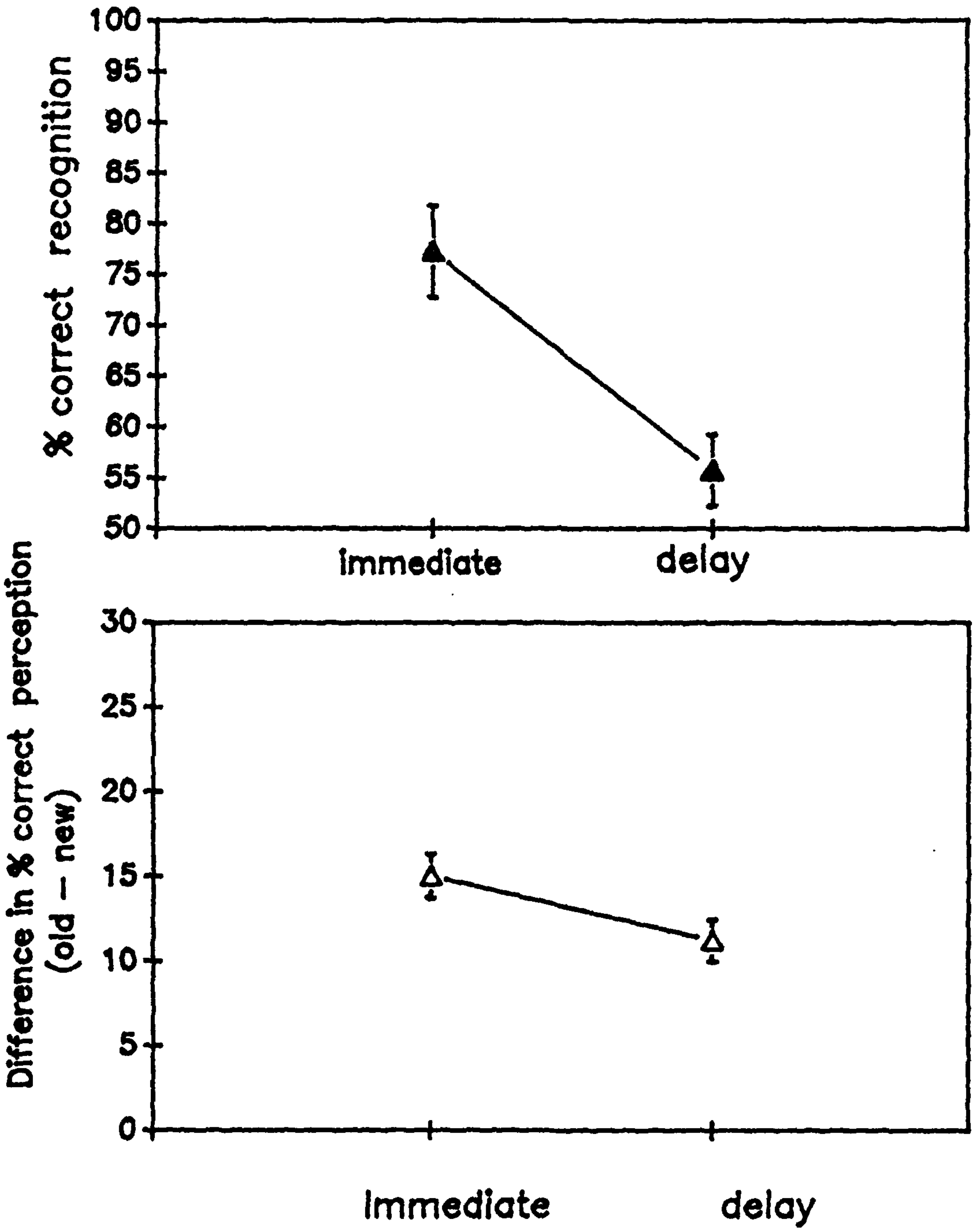
(a)
% patterns correctly perceived
old
new
Day 1
Day 2
Day 10
Day 40
(b)
% patterns correctly perceived
old
new
Day 1
Day 8
Day 40
(c)
% patterns correctly perceived
old
new
Day 1
Day 8



100
90
80
70
60
50
% correct recognition
immediate
delay



30
25
20
15
10
5
0
Difference in % correct perception (old – new)
immediate
delay


100
95
90
85
80
75
70
65
60
55
50
% correct recognition
immediate
delay
30
25
20
15
10
5
0
Difference in % correct perception
(old – new)
immediate
delay

Recognition (R) \ Perception (P)	+	−
+	PR	$\bar{P}R$
−	$P\bar{R}$	$\overline{PR}$